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Evaluation of tactile situation awareness system as an aid for improving aircraft control during periods of impaired vision

Brown, James S.

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

EVALUATION OF TACTILE SITUATION AWARENESS SYSTEM AS AN AID FOR IMPROVING AIRCRAFT CONTROL DURING PERIODS OF IMPAIRED VISION

by

James S. Brown

June 2009

Thesis Advisor: William Becker
Second Reader: Michael McCauley

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James S. Brown
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1995

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Author: James Shelton Brown

Approved by: William Becker
Thesis Advisor

Michael McCauley
Second Reader

Mathias Kölsch
Chair, MOVES Academic Committee

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LIST OF ABBREVIATIONS AND ACRONYMS

AAV	Autonomous Aerial Vehicle
ACS	Aircrew Systems
AOPA	Aircraft Owners and Pilots Association
CAVE	Cave Automatic Virtual Environment
CNN	Cable News Network
DEG	Degrees
EAI	Engineering Acoustics Incorporated
FAA	Federal Aviation Administration
FAR/AIM	Flight Air Rules and Aeronautical Information Manual
FY	Fiscal Year
GPS	Global Positioning System
GUI	Graphical User Interface
HARS	Human Abilities Requirements
HCI	Human Computer Interfaces
HRS	Hours
HSI	Horizontal Situation Indicator
IG	Image Generator
IP	Internet Protocol
IRB	Institutional Review Board
ISS	International Space Station
LCD	Liquid Crystal Display
LZ	Landing Zone

MSL	Mean Sea Level
NARG	Naval Aviation Requirements Group
NATO	North Atlantic Treaty Organization
NATOPS	Naval Air Training and Operating Procedures Standardization
NVG	Night Vision Goggles
OPNAVINST	Operational Naval Instruction
POM	Program Objective Memorandum
SEC	Seconds
TSAS	Tactile Situational Awareness System
THA	Tullahoma Tennessee Regional Airport
UDP	User Datagram Protocol
USA	United States Army
USAF	United States Air Force
USB	Universal Serial Bus
USN	United States Navy
VIRTE	Virtual Training Environment
VFR	Visual Flight Rules
VSI	Vertical Airspeed Indicator
YRS	Years

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Thank God for the strength, patience and opportunity to contribute to the area of modeling, virtual environments and simulation. Support and encouragement from loving parents and family established the foundation to reach this milestone. To Gail, my beautiful wife, and our children Elizabeth, Abigail, James, and Sian, the journey was challenging and ultimately rewarding thanks to your loving support and excusing the countless hours required while completing this goal. Thanks to Dr. Becker and Dr. McCauley for allowing time necessary for family priorities and providing the correct mix of technical advice and guidance. Thanks to the University of Central Florida for the interagency exchange of the research Tactile Situation Awareness System (TSAS). Mr. Jeff Knight, your electronic assistance in Bullard Hall Lab was great. To Mr. Randy Jones, thank you for your Python software assistance and troubleshooting support with the interface during code design. Finally, thanks to the Office of Naval Research, Virtual Training Environment (VIRTE) Program for sponsoring portions of this thesis.

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I. INTRODUCTION

A. BACKGROUND

In aviation, there is a concern that laser blinding could cause pilots to crash because of an inability to see. The pilot has to know how to interact and manage time with the aircraft, crewmembers, weather conditions, other aircraft, birds and personal flight equipment. As for the flow of tasks, the pilot interacts with the aircraft, the environment, and the airspace. The pilot is constantly scanning instruments, manipulating controls, and listening for alarms. For each of the three areas, vision is the source of information the pilot used to gather necessary information for stabilized flight. A proposed solution to the laser problem is to test pilots wearing the Tactile Situational Awareness System (TSAS) as an aid to continue controlled flight after losing visual references outside the cockpit and to flight instruments.

The hope is that, using the TSAS, the pilot will be able to fly safely to a landing zone, saving lives and aircraft. According to Brooks and Madden of CNN (2005), the threat from potential laser blindness is increasing. It occurs when a pilot is on final approach to an airfield and reports a laser light pointed at the aircraft cockpit. Fortunately, no cases of laser activity have resulted in an aviation accident to date. However, should the laser have the appropriate power to blind a pilot, such a situation could be catastrophic. TSAS could be useful during a blinded pilot situation to cue the pilot to maintain aircraft orientation and fly safely to a landing zone.

B. MOTIVATION

According to Nakagawara (2003), pilots use vision for over 90 percent of input cues in command and control of an aircraft. Visual cues allow quick updates for hand-to-eye coordination in the cockpit and help pilots perform their jobs with ease. Visual information has become an information single point of failure for pilots. Unfortunately, there is not a fielded device to substitute for the required high scan rates, or to allow a pilot to receive information and monitor critical flight instruments and alarms in the cockpit in the event vision is lost.

Procedurally, military manuals such as Naval Air Training and Operating Procedures Standardization (NATOPS) manuals and the Federal Aviation Administration Flight Air Rules and Aeronautical Information Manual (FAA FAR/AIM) do not cover or adequately address how to handle this situation—except to gain altitude, engage the autopilot if available and wait for vision to return and file a pilot report.

Currently, primary flight training programs do not incorporate the use of the TSAS for pilot training. However, the technology and concept exist. The TSAS affords pilots a tool to aviate when experiencing reduced visibility.

C. MODELING TOOLS TO SIMULATE FLIGHT ENVIRONMENT

The MOVES Lab contained a simulated flight-training device. By feeding data from the flight training device computer to the TSAS and developing an appropriate software interface program, simulated flight with the TSAS was feasible. This approach provided a mechanism to record flight data during a simulated laser-blinding emergency. Collected data resulted in measured performance of Participants with the TSAS during simulated vision loss to the pilot in a virtual flight environment.

D. OBJECTIVE AND HYPOTHESES

The objective was to record and compare participant performance level with and without the TSAS following a simulated laser-blinding event, using a virtual helicopter approach and show the value added using the TSAS. Furthermore, the military and the aviation industry gains another set of data to strengthen the case for developing more cockpit instrumentation systems based on the TSAS in the future.

The researcher explored three hypotheses concerning the use of the TSAS in this thesis. First, the TSAS augments degraded or lost vision during an approach. Second, the TSAS can provide feedback following laser blindness and inform the pilot how to navigate the aircraft toward a specified landing zone in the absence of visual cues. Third, the TSAS can function as a haptic instrument for maintaining controlled flight in a virtual environment. Finally, what, if any, are the new negative consequences added using the TSAS, which could affect safety of flight?

E. THESIS OUTLINE

The layout of this thesis is as follows: Chapter II provides background and literature review. Chapter III describes the methods, procedures, and experimental setup. Chapter IV presents results based on data retrieved from X-Plane for each participant and the results from participant post-questionnaire. Chapter V discusses the conclusions, reports if the TSAS was an effective haptic flight instrument for flight, describes the limitations of the thesis, and provides a list of potential paths for continued future work to explore other potential applications with the TSAS.

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II. LITERATURE REVIEW

A. HAPTIC SENSES

Why consider a haptic sensor display? Before addressing the design, a brief background on the interaction of the human body and haptics is necessary. According to Gibson (1966), the sensibility of the individual interacting with the world adjacent to the body occurs through the response of nerve and pressure sensors on and beneath the body's largest organ, the skin. Therefore, the largest organ the skin functions as one large haptic system. According to Geldard (1972), the skin is receptive to stimuli including changes in temperature, pain, and pressure. In this thesis, the focus is on the flight environment in which a rubberized Body Glove™ vest lined with haptic input devices interacts with the body, providing cueing information about the state of the aircraft in the absence of sight. Further research by Hendrix and Durfee (2003) explored haptics with Human Computer Interfaces (HCI) as an advantage over visual interfaces. Hendrix and Durfee used Fitt's law to model HCI accuracy and movement.

The interaction medium for this haptic system is the nervous system just below the epidermis and dermis skin layers. The tiny hairs covering the body pass through the epidermis and dermis and connect to nerve endings. The human tactual system provides a proximity sense and the feeling of a stick or prick to the body. The Ruffini corpuscles are the nerve receptacles beneath the skin capable of detecting changes in temperature. The Merkel receptors sense external pressure changes and respond to frequencies from 0.3 Hz to 3 Hz. Velocity fluctuations depend on the Meissner corpuscles under the skin and have a sensitivity range from 3–40 Hz. The Pacinian corpuscles from Anatomy of the Skin (2006) (see Figure 1) classified as the largest skin receptors fit the desired characteristic needed to conduct the experiment. Research by Engineering Acoustics Incorporated state the Pacinian corpuscles are sensitive receptors and respond to input changes primarily in the 200Hz–350Hz zone, allowing high sensitivity to acceleration and vibration from sensor devices like the C-2 tactor placed next to the skin. An added benefit of the Pacinian Corpuscles found by Klatzky and Lederman (2002) is that they are rapid adapting receptors within sub cutaneous tissue and the effect of stimuli to pressure and vibration decays rapidly.

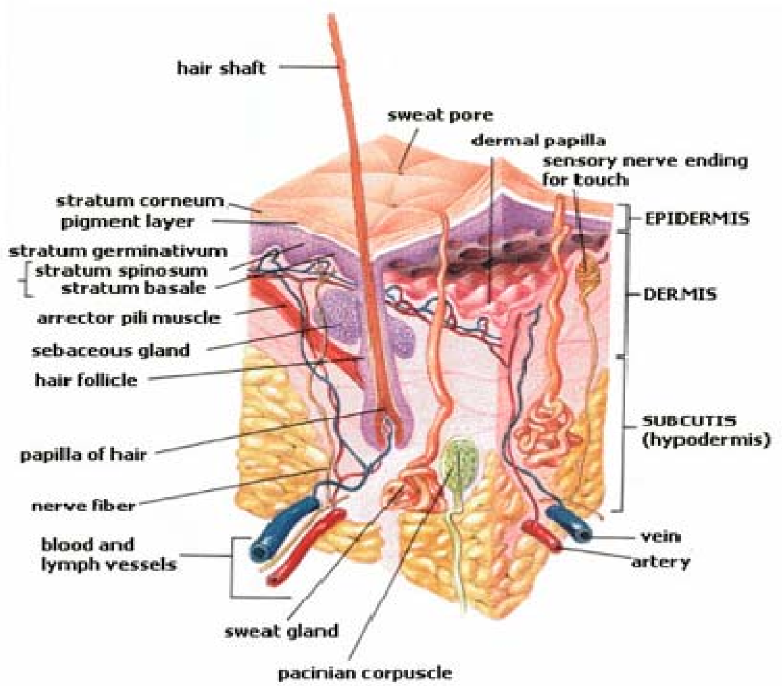

Figure 1. View of Pacinian Corpuscle (From Anatomy of the Skin, 2006)

The TSAS lined with C-2 tactor devices creates a haptic instrument to stimulate the haptic senses. Haptic systems consist of external apparatus by which the individual receives information concerning the state of a platform in an environment through interactions with the body. By using haptics, the pilot stays aware of the information available from cockpit instruments without having to rely solely on vision. Haptics also reinforces awareness of the aircraft attitude because the torso is normally buckled into the aircraft forming perpendicular alignment to the normal of the aircraft, whereas the pilot's head may tilt (Liggett 2002 from Hasbrook and Rasmussen, 1973) skewing the relationship of the aircraft to the horizon.

B. LITERATURE REVIEW

Haptics is one of the first senses that humans encounter during development (Gibson, 1966). Booher (2003) defined haptic vision as using a sense of touch to maintain situational awareness of one's surroundings. The application of haptics or tactile devices for flight purposes began in the mid-1990s with proof of concept performed in 1995 in a Cessna 172 (Rupert, 1997). According to Rupert, he designed the haptic piloting device and named it the Tactile Situational Awareness System (TSAS). Naval Air Base Patuxent River conducted military test of the TSAS using a T-34C test aircraft in 1995 (Rupert, 1997). Several other TSAS experiments have followed the pioneering work of Dr. Rupert. The Netherlands used the TSAS in a study to reduce side drift while training pilots in the use of night vision goggles (NVG) during flight. Researchers Erp, Veltman, Veen, and Oving (2002) of the Netherlands reported students in the Royal Dutch Airlines Flight Academy experienced improved night flights during normal and NVG flights while wearing a torso TSAS piloting aid.

The first pneumatically-activated version of the TSAS resembled an aviation harness (see Figure 2). Technology progression allowed a transition from pneumatically-driven tactors to vibro-tactile devices using on board aircraft and backup electrical power (McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004). The pneumatic version required bulky connections and an air pump to supply the air for the tactors inside the vest.

Figure 2. Pneumatic style TSAS for Military Aircraft (After McGrath et al., 2004)

Non-aviation variants of the TSAS are in use. Divers used haptics to navigate through murky water to reach waypoints under the sea and along coastal regions (Erp, Veen, Janseen, & Dobbins, 2005). An Astronaut demonstrated the TSAS ability to assist with maintaining orientation with the International Space Station (ISS) while performing extra-vehicular activities (Erp and Venn, 2003). Research by Cardin, Vexo and Thalman (2006) support the use of the TSAS as a flight station alarm remote indicator. Cues from the TSAS alerted the off-duty pilot during long transatlantic or transpacific flights if an alarm sounded or the other pilot at the controls needed assistance.

How can the TSAS help in aviation? One possible goal is to help reduce CLASS A mishaps. According to Operational Naval Instruction (OPNAVINST) 5100.23G, CLASS A mishaps, also known as Category 1 and catastrophic accidents, are those resulting in a total of one million dollars or more in material property damage, a fatality, or permanent total disability. Mishaps having degraded vision as a factor fall into the spatial disorientation category. Unfortunately, spatial disorientation, when reported in aircraft mishap investigations, receives a classification of *pilot error* as the causal factor (Shender, 2004). General Aviation pilots have a higher number of Class A mishaps. From 1983 to 2007, the National Transportation Safety Board (AOPA 2008) recorded 744 fatal accidents for the General Aviation Community. The need for reducing the number of Class A mishaps has reached the congressional level, and a goal set by the Secretary of Defense under Department of the Navy Objectives for 2006 was a reduction in the baseline number of Class A mishaps by 75 percent before the end of fiscal year (FY) 2008. Furthermore, the number of acceptable Department of Defense losses is zero according to Mr. Christopher Bolkcom (a specialist in national defense, foreign affairs, defense and trade division, congressional research service), during testimony to the 108th Congress February 2004 on aviation safety initiatives. Increased aircrew safety and the prevention of aircraft loss caused by human factors are potential benefits obtained using the TSAS as an instrument.

According to Nakagawara et al (2003), the Department of Transportation and the FAA in 2003 conducted a critical flight zone test in a controlled simulated environment to test the effects of increased laser illumination on terminal operations with eye safe levels of power between 0.5 and 50 Microwatts per square centimeter ($\mu W/cm^2$). The FAA concluded that within 30 seconds, a pilot with exposure to a laser regained vision sufficiently to perform flight operations. However, above 50 Microwatts, the effects were serious. Thus, there is a need for the functionality of the TSAS to augment vision and allow the pilot to maintain flight until safely over a suitable landing field. Ultimately, the TSAS adds a haptic interface for the pilot to help minimize vision-induced mishaps in planes and helicopters. Reducing visual instrument scans inside the cockpit during high workload flight operations allow more attention outside the cockpit.

Several operational and psychophysiological surveys collected on USAF, USN, USA, Hellenic Air Force and the United Kingdom pilots and consolidated by the North Atlantic Treaty Organization Research and Technology Organization (2005) support the impact of spatial disorientation from the lack of visual cues. All aviation forces within the U.S. services and the surveyed North Atlantic Treaty Organization (NATO) countries listed visual effects such as blending of earth and sky, not detecting side drift for helicopters, the leans, misleading attitude cues from instruments, loss of horizon during instrument meteorological conditions, and distractions because of task load as factors contributing to safety of flight.

The TSAS has not become a common application in cockpits. Reports by pilot subjects exposed to older TSAS models demanded better tactor technology, better integration and miniaturization of components. Insufficient cooling causing discomfort while wearing the TSAS with flight gear limited the use of the TSAS in one study (McGrath, Estrada, Braithwaite, Raj and Rupert 2004).

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III. METHODS AND PROCEDURES

A. PARTICIPANTS

The Institutional Review Board (IRB) granted an IRB approval letter for the proposed research (Appendix D). Nine Participants volunteered after responding to student body email, MOVES Brown Bag lectures, and announcements from previous instructors.

B. PRE-FLIGHT QUESTIONNAIRE

The Pre-Flight Questionnaire (Appendix B) contained questions designed to determine if a Participant was susceptible to simulator sickness and to help collect level of flight experience. One question asked the Participant about the TSAS and possible training benefits. This question was designed to determine if knowledge of such a device was reaching aviators. All Participants received a summary of the experiment and signed a Participant consent form outlining their rights to participate and the request to stop the experiment at any time. Time to train prior to the scenario was determined from data collected on the questionnaire. Non-pilots required more familiarization with the controls, whereas experienced pilots did not. Both groups required the same amount of familiarization with the TSAS because none of the Participants had any prior experience using such a device.

C. APPROACH TECHNIQUES

Approach occurs when the helicopter transitions from level forward flight, descends to a hover over a landing zone, and lands. The helicopter approach process has four segments the pilots must master: approach angle, rate of closure, power control, and landing.

Approach angle is typically eight to ten degrees down pitch from the horizon and appears steep to fixed wing pilots who normally are familiar with a standard three-degree approach on glide slope common with most instrument approaches. The procedure commences by establishing an eight-degree to ten-degree approach angle, which can be visual or assisted by runway lighting systems. The pilot maintains the approach angle by performing a pitch adjustment for the angle of descent and establishing a view of the field or landing zone (LZ) through the windshield. Constant speed is not a factor since helicopters do not stall at low speeds as in fixed wing aircraft. Helicopter pilots monitor groundspeed and the landing skids alignment with the LZ while on approach to prevent rollover. By manipulating the collective, they control sink rate read from the vertical airspeed indicator (VSI) or by visually judging rate of descent. The landing skids are the landing gear or rails under a helicopter on which it lands. The VSI provides the pilot a display of vertical rate in feet per minute as the aircraft climbs or descends. Approach operations place the helicopter close to the "back side of the power curve," which is the point if entered yields no response from the aircraft regardless of power adjustments via the collective. The speed of the approach starts between 40 and 50 knots airspeed and terminates in a hover. For inexperienced pilots, defined as less than 20 hours in type aircraft, the hover may occur early before arriving over the intended landing point. Because the angle of approach shifts from a ten-degree approach to a pitch up or flared attitude, pilots push forward on the cyclic to continue the approach and to avoid the chance of the helicopter's tail rotor striking the ground. Finally, in termination, the pilot completes the approach by ensuring the helicopter is in a level hover or slightly forward motion with the landing skids. Alignment of the skids with the LZ is necessary to prevent a rollover should the helicopter approach too quickly and is not aligned with the direction of travel. Voice communications exchanged with approach control prior to termination phase provide vectors to the LZ. Once the approach commences, the pilot switches to tower control, if available, and then to ground control to determine a position to park or refuel.

D. APPARATUS

The research TSAS (see Figure 3) was loaned to the Naval Postgraduate School by the University of Central Florida in Orlando after an experiment to enhance training in a virtual environment for infantrymen during a room clearing procedure (Fowlkes, Washburn, Eitelman, Daly, & Cohn, 2006). A quarter placed next to the bottom center C-2 tactor (see Figure 3) illustrates the relative size of each tactor.

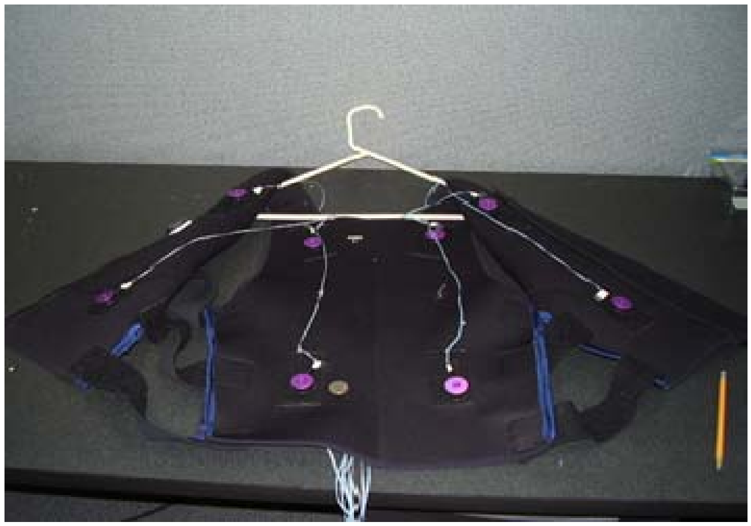

Figure 3. TSAS Courtesy of University of Central Florida (From Brown, 2007)

Engineering Acoustics Incorporated (EAI) manufactured the C-2 tactors (see Figure 4) used as the cueing devices for the pilot.

Figure 4. C-2 Vibro-tactor by Engineering Acoustics, INC (enlarged photo).

The TSAS consisted of a vest garment and with leg straps. The tactors lining the TSAS vibrated according to programmed flight parameters based on selected simulated flight environment. The wearer, who is taught the relationship of the haptic stimuli with the flight instruments, then performs a control input to continue flight.

E. PROCEDURE

A time of forty-five minutes was determined as the requirement for each participant to complete the experiment using the MOVES CAVE Flight simulator. Phase 1 provided training to fly the simulator for inexperienced and experienced pilots without the TSAS. Next, all Participants were familiarized with the operation of the TSAS during a fitting session and to experience the cues received from the TSAS within a normal flight environment. Roll cue familiarization required the Participants to place the aircraft in a roll that exceeded positive or negative seven degrees and recognize the corresponding TSAS correction cues. Roll and pitch values selected were based upon staying within normal maneuvering flight envelop as described in approach techniques and to ensure positive flight control inputs from pilot was required to maintain safe flight. During pitch familiarization, the Participant received feedback cues if a nose high pitch of 20 degrees occurred or a dose down pitch exceeding negative eight degrees occurred. Anti-torque or rudder pedal cues were provided to the participant via upper thigh cues if the aircraft heading changed by more than one degree. During Phase 2, the Participant wore the TSAS in a degraded vision state. This phase measured Participant performance while navigating toward the landing zone and during a TSAS assisted approach. The scenarios required the pilot to experience a loss of vision state and be able to shift from visual cues to haptic cues with no warning. The standard for successful performance was the pilot receiving and understanding cues to navigate to the landing zone without crashing.

F. SCENARIO DESCRIPTION AND TASKS

The flight plan was a business trip to visit the Jack Daniel’s Distillery near Tullahoma, Tennessee. Weather was clear and this was a visual flight rules landing. The visual approach for Tullahoma Tennessee Regional Airport (THA) Runway number Three-Six (36) was the flight environment selected (see Figure 5). Runway 36 corresponds to the closest magnetic heading of 360 degrees. The simulated location was ideal because all the terrain for the landing field from X-Plane synchronized with Delta-3D graphics that allowed displaying the terrain in the MOVES Institute CAVE. Tullahoma airport elevation was 1083 feet mean sea level. The aircraft contained fuel to conduct one wave off and attempt another approach to the same airfield but not enough fuel to fly to a divert airport. To keep Participants from using instruments and to limit the transition from visual to haptics, the researcher informed all Participants the aircraft was operational and they were flying solely on visual references. All visual approaches commenced four nautical miles from the landing zone.

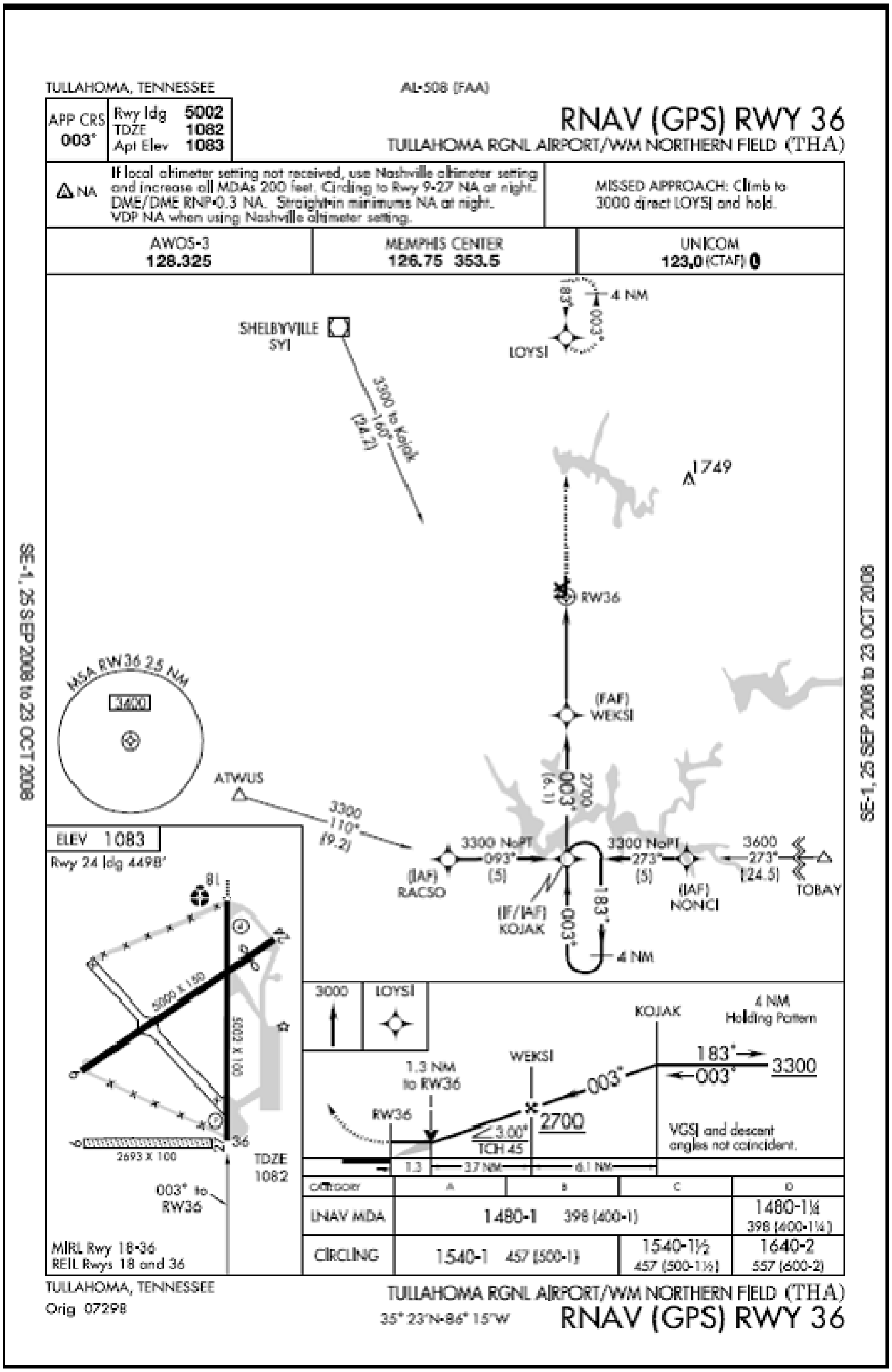

Figure 5. Tullahoma Regional Airport Runway 36

Once the Participant was one nautical mile south of the landing zone, the researcher virtually removed the pilot's vision by pressing the "no-image" button. The geographic location south of the landing zone received the name "incident point." Incident approach point placed the aircraft 800 feet above ground level or 1883 feet mean sea level. Incident point was determined based on the aircraft's approach altitude and heading. When reaching Incident Point, the assumed laser event with sufficient power blinded the pilot. Blinding was based on the assumption that protective lenses or helmet visor were not worn. Once this incident occurred, the user continued flight without visual cues. The researcher disabled X-Plane voice communications in each phase. The pilot, with or without the TSAS, was instructed by the researcher to continue and attempt to reach a safe landing zone using only memory of visual references prior to the incident. With the TSAS, haptic cues corresponding to aircraft control input corrections directed the user to the field. In the virtual environment used, no motion was available to the pilot to sense aircraft forces or the forces of gravity and maneuvers. To add some virtual immersion, the available audio system in the MOVES CAVE amplified simulated aircraft sound effects created by X-Plane.

Half of the Participants used TSAS first and half experienced the "No TSAS" condition first. Once the instruction and familiarization phase for the training device was over, the Participants tried on the TSAS around the torso and received instruction on the cues the TSAS would provide during flight. The tactors received input signals based on X-Plane data activated by pitch, roll, and heading set points programmed into the code in Appendix A. The input signal drove the appropriate C-2 tactor and provided cueing feedback from the cockpit instruments to the pilot. The cues were intended to help the pilot maintain heading, and normal pitch and roll attitude, while approaching a landing zone. The Participants performed the following tasks:

1. Maintain control of the aircraft by maintaining altitude and keeping the horizon level.

2. Continue to landing zone using TSAS inputs.

3. Perform a haptic visual approach using the heading cues to landing field with the TSAS.

4. Provide feedback after Phase 2 on post event questionnaire.

The roll cues corresponded to signals from the upper left and upper right front tactors and indicated left cyclic or right cyclic inputs, respectively. Tactors positioned at the left and right upper back corresponded to aircraft pitch corrections based on limits chosen in Appendix A. The TSAS contained two connections that provided the user with cues from Velcro strapped leg tractors on each leg. When the user received a cue, the user applied either left or right anti-torque pedal inputs to steer back and maintain the aircraft on the desired heading toward the landing zone. The two tactors on the lower front were intended for collective or power inputs but not used. Two tactors on the lower back of vest were in place as spares in case one of the other tactors malfunctioned. The small number of tactors used enabled Participants to understand and remember the meaning of the tactor inputs necessary to perform the mission.

G. RADIAL OR HEADING KEEPING DURING APPROACH

Radial or heading keeping normally involves the use of a single navigation receiver dialed up to a radial on a navigation aid or magnetic fix by which the pilot can locate an airport or a landing zone. The process requires the pilot to make adjustments to keep the aircraft on the radial and monitor aircraft position until safely landing. The process consisted of a constant feedback information loop designed by the researcher especially for this thesis (see Figure 6).

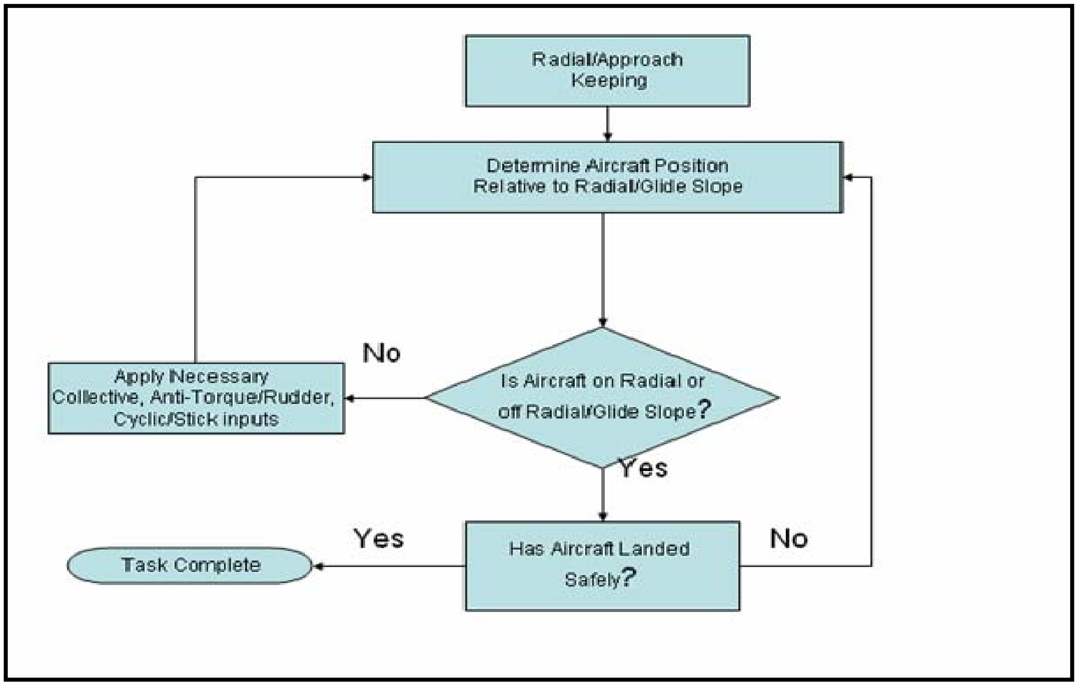

Figure 6. Radial Keeping to Landing Decision Flow Path

From the radial keeping flow path, signals programmed into the TSAS interface box provided the participant with a cue indicating whether the aircraft flew left or right of the desired heading or navigation radial.

H. HUMAN ABILITIES REQUIREMENTS (HARS)

In order to illustrate the dependency on vision and why a TSAS could prove beneficial, a task analysis and human abilities requirement (HARS) analysis was conducted. The requirements and frequency of cognitive, motor and perceptual tasks required to conduct a visual approach in a virtual simulator environment appear in Table 1.

	Altitude Recognition	Deductive Reasoning	Inductive Reasoning	Memorization	Speed of Closure	Flexibility of Closure	Perceptual Speed	Spatial Orientation	Visualization	Tactor Input Recogniton	Hand Steadiness	Foot Input	Control Precision	Multilimb Coordination	Visual Eye Scan	Rate Control	Reaction Time	Speed of Limb Movement	Near Vision	Far Vision	Visual Color Discrimination	Peripheral vision	Depth Perception	Tactor Feeling Sensitivity
	COGNITIVE										**MOTOR**								**PERCEPTUAL**					
MAINTAINING HOVER/ALTITUDE																								
Change Input to Collective	●	●	●			●	●	●	●	●	●		●	●	●	●	●	●	●				●	
Apply Appropriate Anti-Torque/Rudder Inputs	●	●	●			●	●	●	●	●		●	●	●		●	●	●	●				●	●
Read Altitude from instruments		●	●		●		●	●							●				●				●	
Recognize Changing altitude	●	●	●	●	●		●	●	●	●					●				●	●			●	●
Scan Instruments				●	●	●		●							●				●					
Aircraft Trimmed	●	●						●	●	●		●		●	●				●	●		●		●
VISUAL/INSTRUMENT APPROACH																								
Recognize Radial for Approach		●	●	●	●	●	●	●	●	●			●	●	●	●	●			●	●	●		
Adjust Anti-Torque Pedal to Stay on Glide Path	●			●			●	●	●	●		●	●		●		●	●		●	●		●	●
Make Decision to Transition to Landing	●	●	●		●		●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●
Check for Descent Rate	●	●			●	●		●	●	●					●	●				●		●	●	●
Adjust Collective		●	●					●	●					●	●	●							●	
Maintain Position on Glide Path				●				●		●	●			●	●	●				●	●			

Table 1. HARS Table with Frequently Linked Items Identified by a Dot

Next, the subtask in the left column of Table 2 display the score based on counting the dots required for the task from Table 1. The ranking of the subtasks coincided with all aviation training, stressing the need to aviate first, navigate, and then communicate with crew and outside agencies such as air traffic control, approach, tower, and ground control.

SUBTASKS	CATEGORIES			
MAINTAINING DISTANCE FOR HOVER/AITITUDE	Cognitive	Motor	Perceptual	TOTAL *
Change Input to Collective	8	6	2	16
Apply Appropriate Rudder Inputs	8	6	3	17
Read Altitude from instruments	5	1	2	8
Recognize Changing altitude	9	1	4	14
Scan Instruments	4	7	1	12
Aircraft Trimmed	5	3	4	12
Instrument Approach				
Recognize Radial for Approach	9	5	3	17
Adjust Rudder Pedal to Stay on Glide Path	6	5	4	15
Make Decision to Transition to Landing	7	8	6	21
Check for Descent Rate	7	2	4	13
Adjust Collective	4	3	1	8
Maintain Position on Glide Path	3	4	2	9
Communicate with Tower/ATC	3	2	3	8
* Scores Based on Count Sum of Categories and Correlate to Training Adage of Aviate, Navigate, Communicate				

Table 2. HARS Frequently Linked Totals

Table 3.

I. DESCRIPTION OF EXPERIMENTAL SETUP

1. MOVES CAVE Simulator Setup

The MOVES lab flight simulator was suitable for the needs of this experimental evaluation. The simulator uses a commercially available software package called X-Plane, which was licensed to NPS. The FAA accepted X-Plane in 2002 as a simulation tool certified to meet Part 61:4(a) and Part 141.41 requirements for a Level 2 Flight Training Device. The MOVES CAVE Flight Simulator (see Figure 7) system required system startup, data recording, and system shutdown procedures.

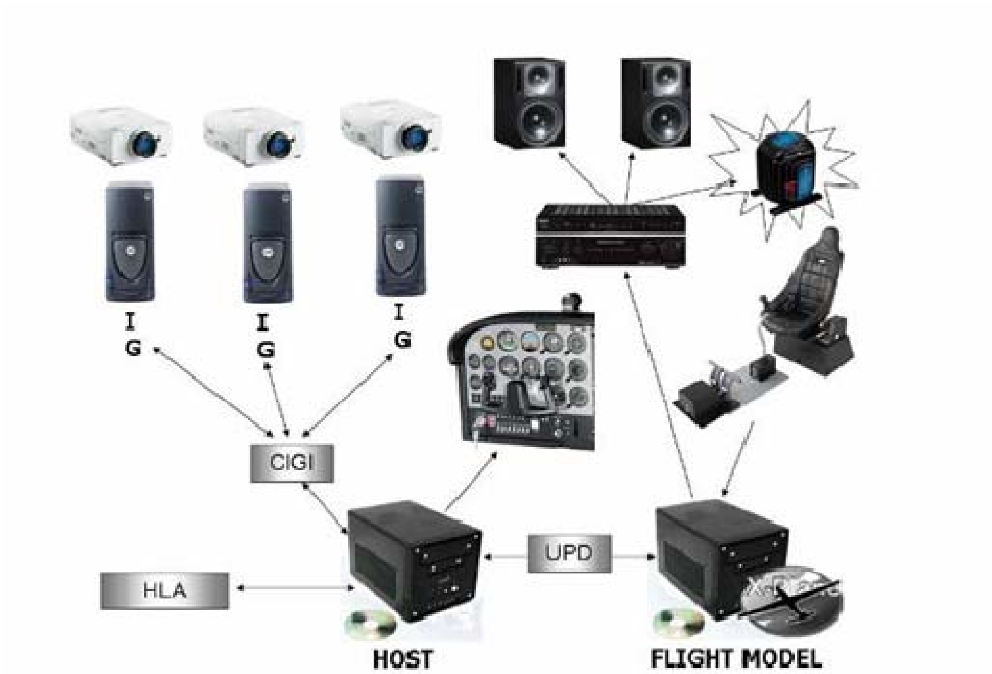

Figure 7. MOVES CAVE Components Photo Courtesy Delta-3D.org

During startup, the Common Image Generator Interface or (IG), an Open Source game engine, provided the visual graphics for the viewer. The IG graphics projected video on three 7-square-foot screens to create a sense of immersion for the simulated flight environment. The researcher monitored the same images using a remote triple-head Liquid Crystal Display (LCD) to monitor the flight with and without the TSAS. The Host computer, Flight Model computer, and Audio System pictured in Figure 7 controlled operation of the CAVE. The Host system supported an instrument gauge operation using a driver package called “TRC Custom” developed by Erik Johnson. The Flight Model computer ran X-Plane version 7.5. The audio system consisted of an Onkyo Stereo receiver, a Klipsch pre-amp, Buttkicker™ amplifier and GENELEC™ speakers.

The flight instrument panel consisted of the basic instruments for flight in a helicopter. They were the compass, altimeter, airspeed indicator, horizontal situation indicator (HSI), vertical speed indicator (VSI), single navigational aid, and a two-minute turn indicator (see Figure 8).

Figure 8. MOVES Flight Research CAVE

Once powered up, the researcher used X-Plane data menus to select the parameters for recording. This required using the X-Plane Settings and Data Input/Output menu accessed from the drop-down menu bar. The process required choosing which computer to serve as the receiving unit and determining whether another computer would duplicate the data based on internet protocol (IP) address. Altitude, Heading, Latitude, Longitude, Pitch, and Roll parameters were selected. The update rate of the data was adjusted to minimize the amount of data recorded while insuring a minimum 15 frames per second rate to maintain a quality virtual environment — and reduce the chance of simulator-induced sickness. Analyzing tool eXaminer version 1.0 was used to review the type of data collected from the X-Plane computer User Datagram Protocol internet protocol (UDP IP) address and the port number specified (see Figure 9) prior to recording the output.

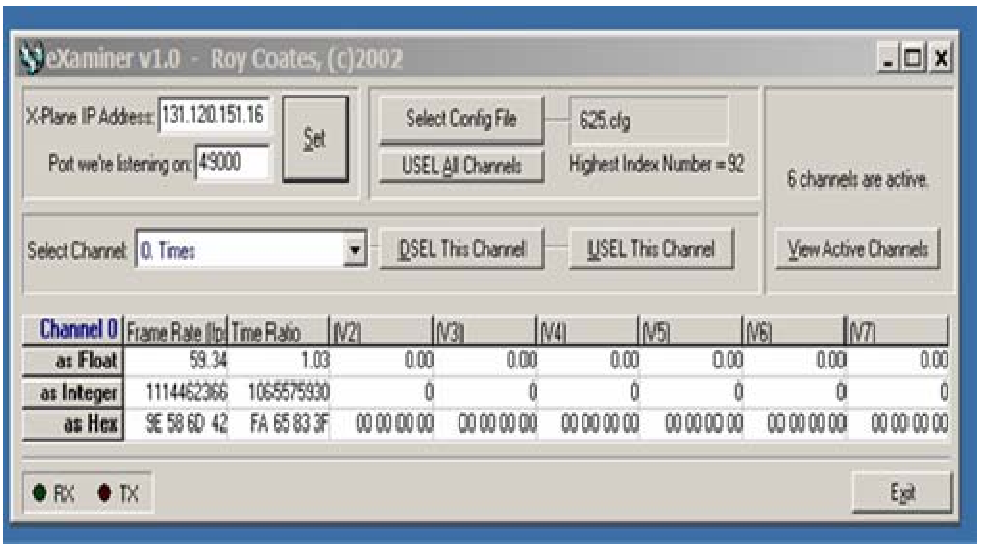

Figure 9. X-Plane eXaminer v1.0 Example Setup

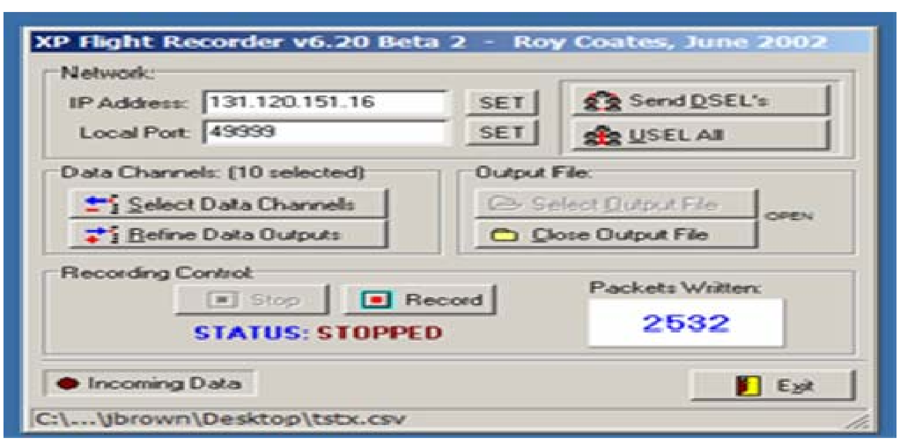

Figure 10. X-Plane Flight Recorder with IP and Port Settings

The use of X-Plane Flight Recorder v6.20 Beta 2 (see Figure 10) shows a typical setup using the IP Address and port number for the sending computer between the host computer and a second computer. This setup became the training setup with the TSAS and recorded the data with text files sent to data.out file extension for archives. To preserve privacy, each data.out file received a file name linked to each participant number. The data contained in the file consisted of parameters marked with an 'x' from the X-Plane Data Input and Output selection menu and the Data sub-menu. The specific index items selected were 00 for the frame rate, 07 for the joystick, 16 for the pitch, roll, and heading values, and 18 for latitude and longitude during flight. The GPS parameter 89 synchronized X-Plane video with the MOVES Institute Virtual Tullahoma Delta-3D scenery.

The next window used under Data Input and Output was the X-Plane Inet sub-menu for data internet UDP protocol address, port assignment, and data send rate adjustable in frames per second. Unfortunately, this window's font was too small to display within the text of this thesis. The last index item on the sub-menu page selected matched the machine IP address of the data receiver machine. This machine contained the code developed to operate the TSAS and perform the initial calibration with the participant.

Since Participants for the experiment came from the Naval Postgraduate School population, time to train each participant to fly was limited and not the primary focus for the research with the TSAS. Therefore, the nullzone of the pitch, roll, and heading from the Flight Line™ stick adjustment reduced the high sensitivity of the controls and made the aircraft more stable (see Figure 11) during the flight.

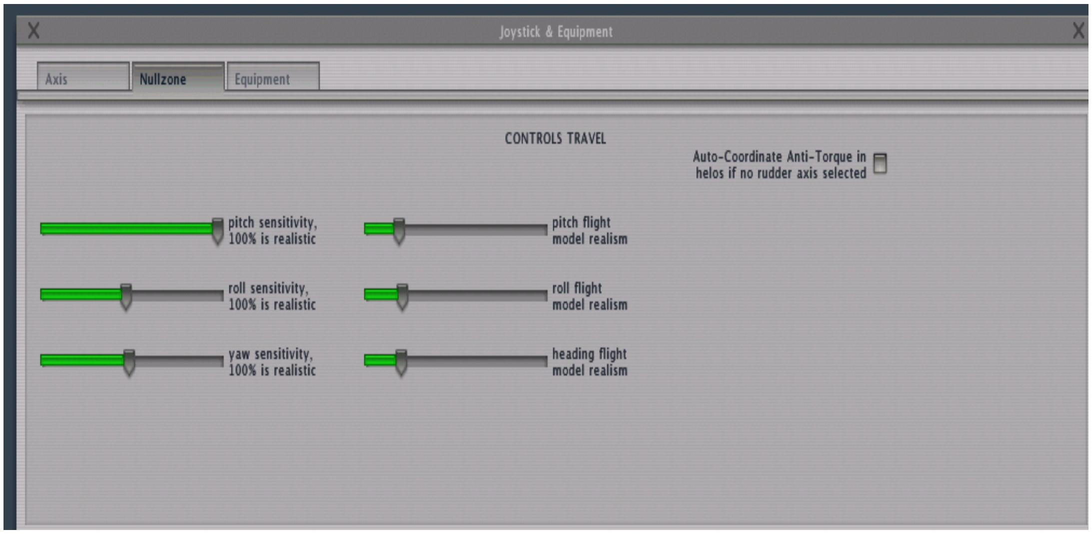

Figure 11. X-Plane Nullzone Adjustment

Shutdown consisted of securing the IG System, Instrument Panel, Audio system, Host and Flight Model computer, Projection system and remote monitor last.

2. Battery Pack Power Supply

Throughout the design phase of the experiment, one safety concern was to remove the requirement for the participant to have commercial power used during the experiment. A battery back provided added mobility without the limitation of an electrical extension cord. Determining the amount of battery power required a power consumption test on the TSAS. The solution was a 12V DC portable battery source. The test indicated a participant could use the battery pack for two hours of continuous operation before the batteries needed replacing.

Using the battery pack for the TSAS during test and calibration in a static environment confirmed full operation while worn with tactors activated. Heat from the interface box using commercial power or a battery pack created a minor safety consideration. Installing a 2.36-inch fan cover satisfied a requirements for participant safety and the protection of the interface fan (see Figure 12).

Figure 12. Tactor Interface Box with Fan Cover Installed

Each C-2 tactor received a unique index parameter assignment to cue the participant based on changes in data received from X-plane. Front and rear drawings of where the C-2 tactors were located on the participant's torso and the corresponding data cue received appear in Figures 13 and 14.

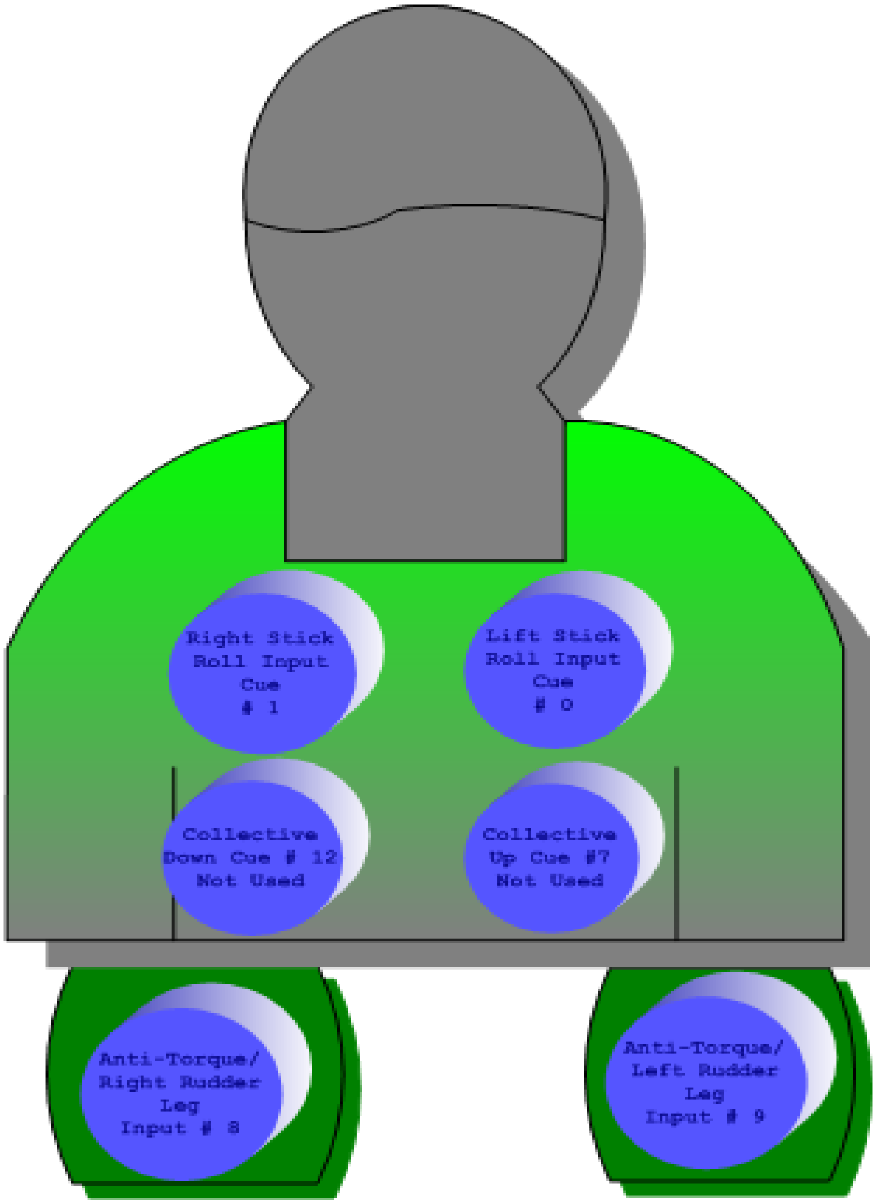

Figure 13. C-2 Tactor Approximate Front Physical Location

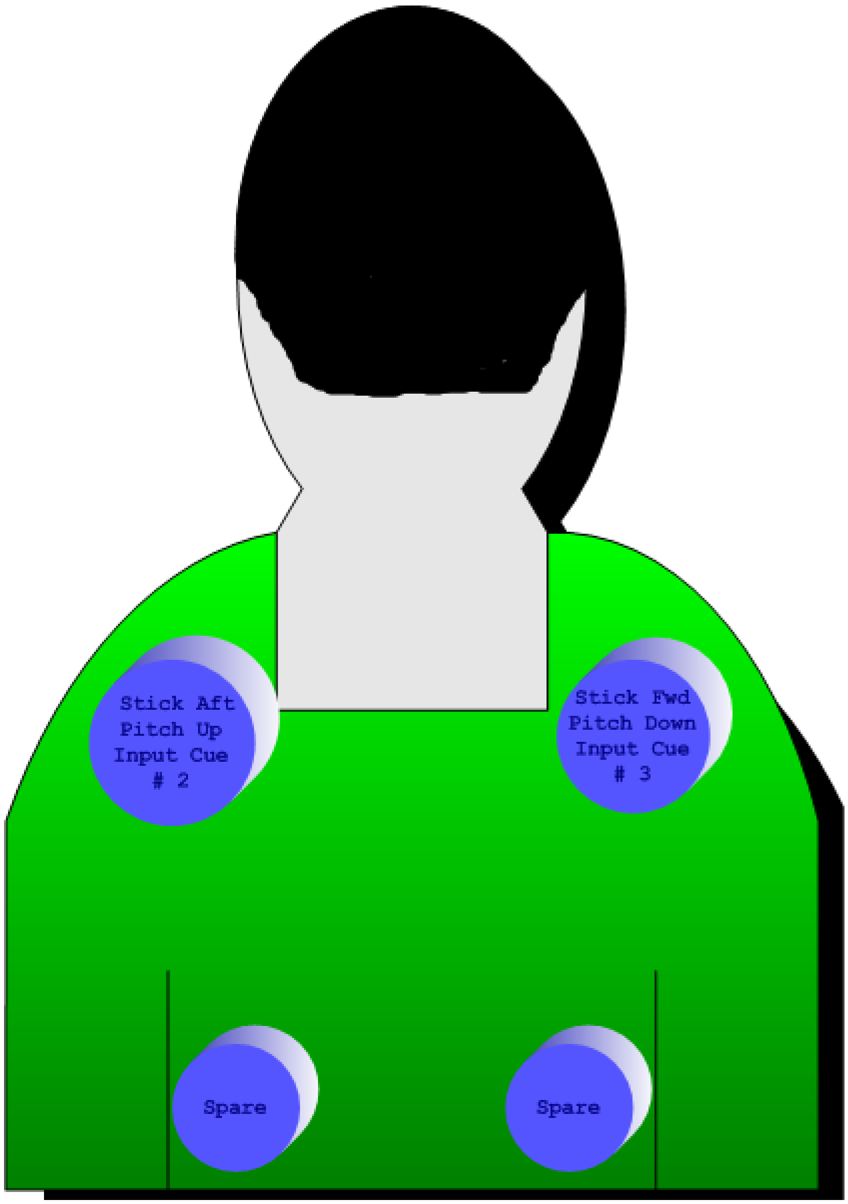

Figure 14. C-2 Tactor Approximate Back Physical Location

J. CODE DEVELOPMENT AND CHALLENGES

Code from the work performed by Fowlkes et al., became a starting point. Initial operation of the TSAS, interface box, and each tactor required the EAI Demo program. This program confirmed that TSAS responded manually without data from X-Plane. Next, the program X-Plane Tactor read data over UDP from the Flight Model machine running X-Plane to the host machine used to drive each TSAS tactor. Duplicate data and command signals for the TSAS traveled from the host computer to the TSAS user through a serial port. The serial port was simpler to implement and excluded the USB port option on the interface panel. The interface allowed assignment of a listening port and a communication port on the receiving computer. This mouse activated graphical user interface (GUI) started data collection — provided the network was up and running and the firewall enabled UDP data.

1. Data Monitoring

The remote station allowed the researcher to monitor the received data in two ways. The first was a window to show the packets received and the second was a program named Portman that recorded and displayed hexadecimal and binary data received. Initially, data received did not result in a response to the assigned tactors on the TSAS. By observing the incoming data, Portman revealed the hexadecimal value-reading format needed to shift the data reading order from Big Endian format to Little Endian format or from left to right as addressed in a text by Null and Lobin (2003).

2. Technical Challenges

Driving each tactor from the data received was a challenge because the values of the X-Plane joystick index ranged from a unit less negative one to positive one for maximum deflection. During simulated flight, joystick deflection stayed between negative decimal five and positive decimal five for normal flight. Precision of data received from X-Plane was excellent because, when printed out from the program, the output was 17 significant digits more than required for recording approach deviations.

Cueing each tactor to provide the necessary correction input was challenging because each tactor needed to be snug against the participant to feel the vibration. Additionally the manufacturer, EAI, recommended an ideal C-2 duty cycle of 10 percent on and 90 percent off. Incrementing the amount of time the tactor vibrated showed the time needed was between 50 milliseconds and 300 milliseconds to ensure proper recognition of tactor input. Providing cues from the TSAS for the anti-torque pedals was achievable by applying a tactor input to each leg for left or right anti-torque pedal input. The input cued the participant to turn toward a particular heading, or was used to prevent yaw tendencies when power was increased or decreased.

Providing the user with cues to counter extreme pitch and roll required reading in data from X-Plane index number 16 and comparing the value received with a tolerance. The port number, communication port, and menu interfaces used to toggle the anti-torque, pitch and roll data from X-Plane to the TSAS appear in Figure 15. The interface prevented overdriving the tactors if X-Plane sent data to TSAS without a user.

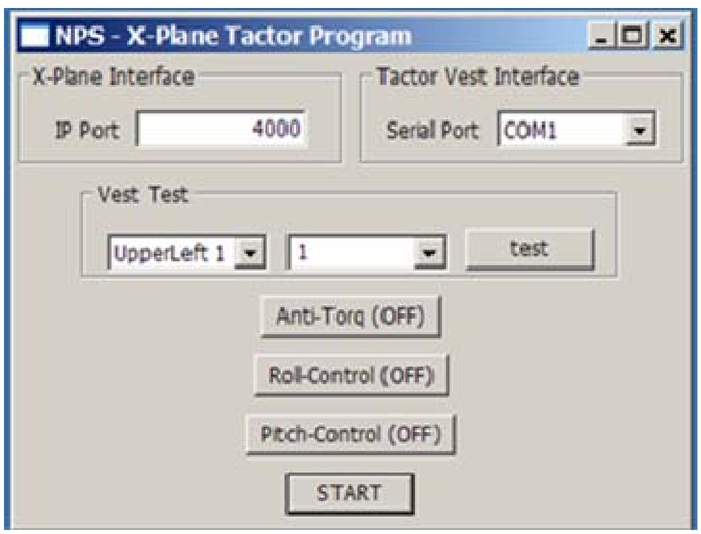

Figure 15. X-Plane to Tactor User Interface

Initial calibration, training, and flying (see Figures 16, 17 and 18) presented technical challenges to achieving the correct virtual refresh rate, while limiting an overload of data recorded for plots and analysis. The remedy required resetting the refresh rate back to 15 frames per second after each reboot of the host and flight model machines. Mapping of X-Plane to the projection screens was possible by using Delta-3D software developed at NPS by the MOVES

Institute Team. The airfield in Delta-3D matched runways in X-Plane for Tullahoma Regional Airport visual flight rules (VFR) final approach.

Figure 16. Calibration Wearing TSAS and Leg Straps (From Sadagic, 2007)

Figure 17. TSAS Training in MOVES CAVE (From Sadagic, 2007)

Figure 18. Flying Simulated SH-60 in MOVES CAVE (From Sadagic, 2007)

If a tactor was non-responsive on the calibration test, a spare was available as a replacement. Barometric pressure adjustments ensured approach altitudes measured in feet mean sea level (MSL) corresponded to the correct height assigned.

IV. RESULTS

A. PARTICIPANTS

The participant sample consisted of eight males and one female. The skill level of the nine Participants consisted of five helicopter pilots, one fixed wing general aviation pilot and three non-pilots. Flight experience among the helicopter pilots averaged 1,590 hours flight time, as noted in Table 3 created from the Pre-Flight questionnaire. Of the nine Participants recruited, six completed all test scenarios with and without the TSAS. Two non-pilots and one pilot participant did not complete the TSAS scenario due to technical problems with the TSAS tactors.

Pre-Flight Questionnaire Data							
Participant Number	**Age(yrs)**	**Gender**	**Dominant Hand**	**Color Blind**	**Flight Experience**	**Flight Time(Hrs)**	**Primary Type**
M71300	44	M	R	N	None	None	None
F80800	53	M	R	N	Yes	4000	Helicopter
M91330	33	M	L	N	Yes	800	Helicopter
M161000	29	F	R	N	Yes	1250	Helicopter
M151400	33	M	R	N	Yes	1500	Helicopter
M151500	31	M	R	N	Yes	1900	Helicopter
F131300	39	M	R	N	None	None	None
F151300	31	M	R	N	Yes	95	Fixed
F191400	34	M	L	N	None	None	None
Average Age, Hours or Count	36.33	8	7	0	6	1590.83	5
Median Age	33.00					1375.00	

Table 4. Pre-Flight Questionnaire Baseline Data

B. MEASURES OF PERFORMANCE

Two measures of performance were collected using the X-Plane flight data from the six Participants completing both scenarios. The first measure recorded the increase in flight time the TSAS afforded the pilot to react and keep the aircraft airborne following a blinding scenario. To calculate the time of each flight, researcher divided recorded frame units by the data collection rate of 15 frames per second. Second, landing zone accuracy comparison with and without the TSAS measured navigation benefit of wearing the TSAS to reach the landing zone after a blinding scenario.

To calculate a paired t-test and paired t-interval, the researcher checked the conditions and assumptions about the data. The measures of performance were on the same Participant before and after use of the TSAS. Behavior by each participant was independent of the others and observed differences were independent. The measured values were random for each individual and the distribution of the differences tended toward normality. Six of the nine Participants successfully completed the events with and without the TSAS. Added flight time with the TSAS was evident using a paired t-test with a $t = 2.695$ with five degrees of freedom and $p = .043$. Results using a difference in time before landing or impact shown in Table 4 support the flight time benefit of the TSAS to allow the pilot from nine to 46 seconds more time for vision to return and continue flight.

Flight Time Before Landing/Impact Using TSAS Compared to Without TSAS			
Participant	**Time With TSAS (sec)**	**Time Without TSAS (sec)**	**Difference (sec)**
M71300	74.1	20.0	54.1
M151500	57.8	50.6	7.2
M91330	67.9	62.1	5.8
F191400	97.3	95.5	1.8
M161000	89.9	42.1	47.9
M151400	88.1	49.1	38.9
		Mean Difference	25.9
		Standard Deviation	21.5
		Standard Error	8.8
		df of 5 at 95%	2.015
		Margin of Error t_5	17.3
		95% confidence	25.9+/-17.3
		or interval of	(8.6,46.2) sec
Results indicate with 95% confident that for pilots wearing the TSAS during an approach flight after a loss of vision on average have between nine and 46 seconds more time in flight than pilots without the TSAS.			

Table 5. Flight Time Gained Using TSAS

Paired t-test using the TSAS for navigation was not statistically significant with a t = -1.33, p = 0.225. Graphical displays of the TSAS approach showed four out of six Participants responded to tactor cues and continued landing zone navigation. Figures 19-24 show the without-TSAS plot line first followed by the with TSAS plot. The zero axes indicate the Participant flew directly over the landing zone. A negative value indicated participant flew past the landing zone. The smaller the difference, the closer the participant flew toward the landing zone.

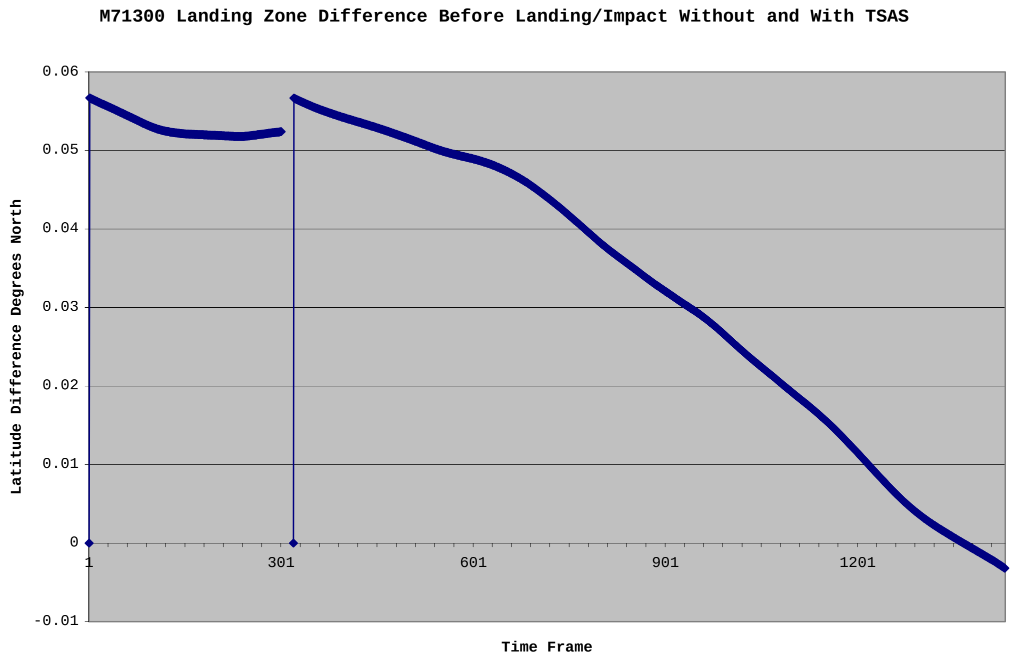

Figure 19. Participant M71300 Landing Zone Difference Plot

Participant M71300 in Figure 19 and participant M161000 in Figure 20 crashed quickly without the TSAS however with the TSAS cueing flew closer to the landing zone.

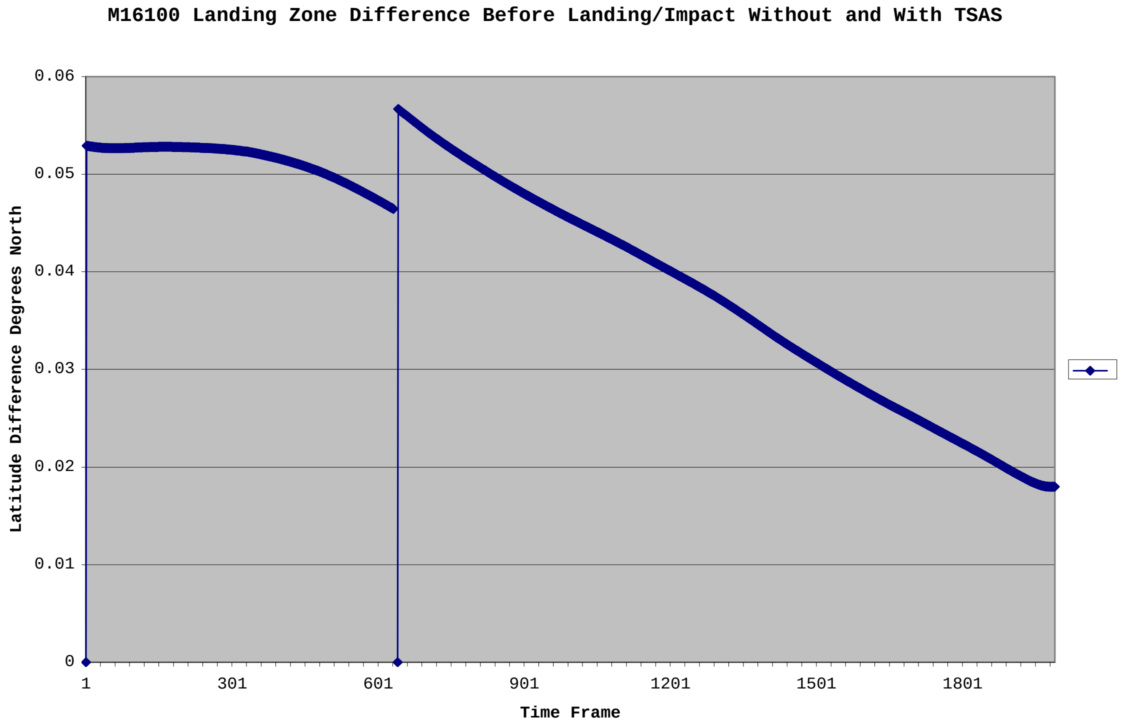

Figure 20. Participant M161000 Landing Zone Difference Plot

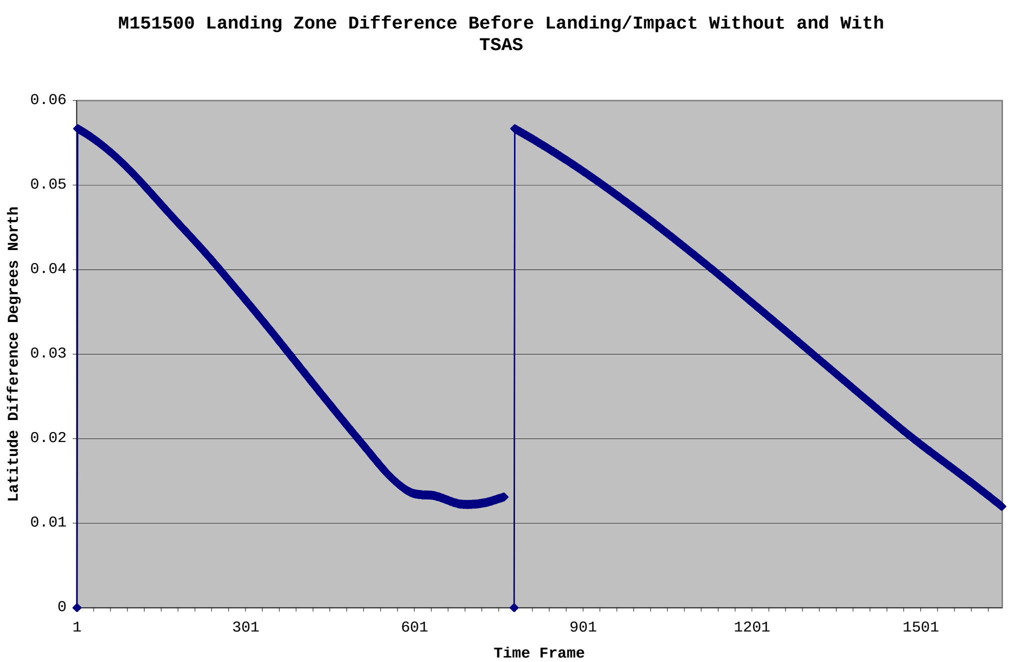

Figure 21. Participant 151500 Landing Zone Difference Plot

Participant M151500 in Figure 21 using the TSAS maintained a direct path toward the landing zone using the TSAS.

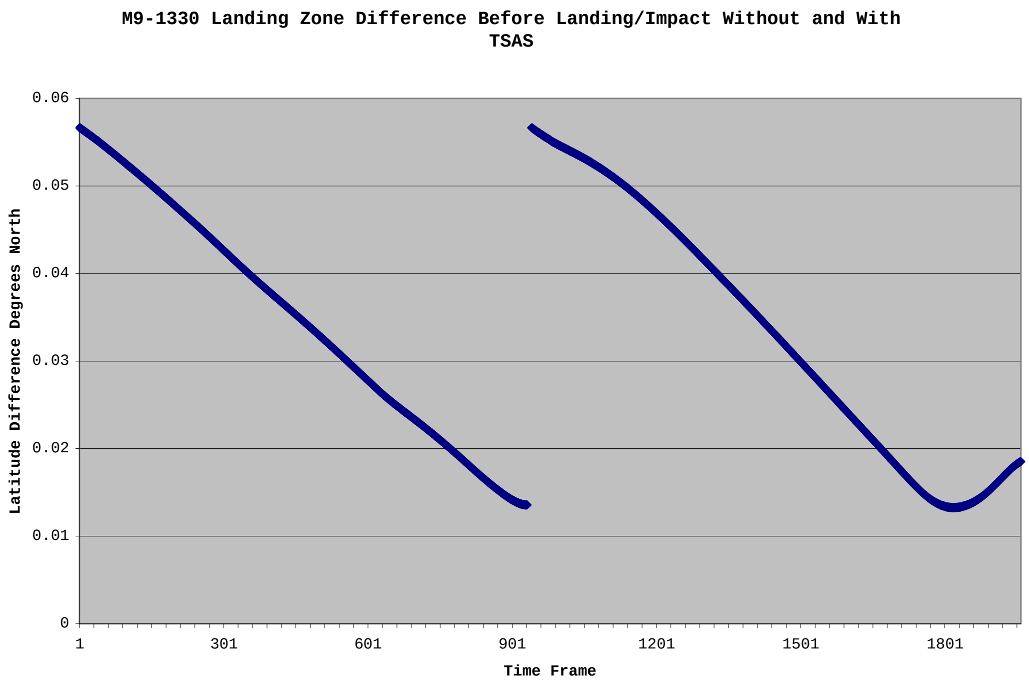

Figure 22. Participant M9-1330 Landing Zone Difference Plot

Figure 22 M9-1330 (see Figure 22) followed a direct path but ended up diverting. Participant indicated experiencing confusion and reverse cueing on post flight questionnaire. Participant M151400 in Figure 23 with TSAS navigated the best of all completing the tasks.

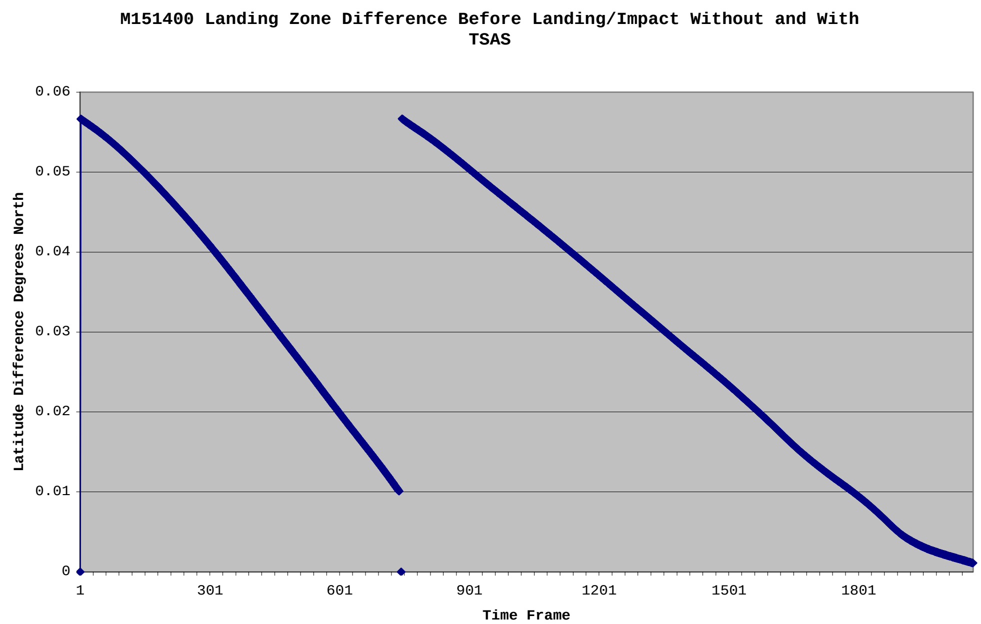

Figure 23. Participant M151400 Landing Zone Difference Plot

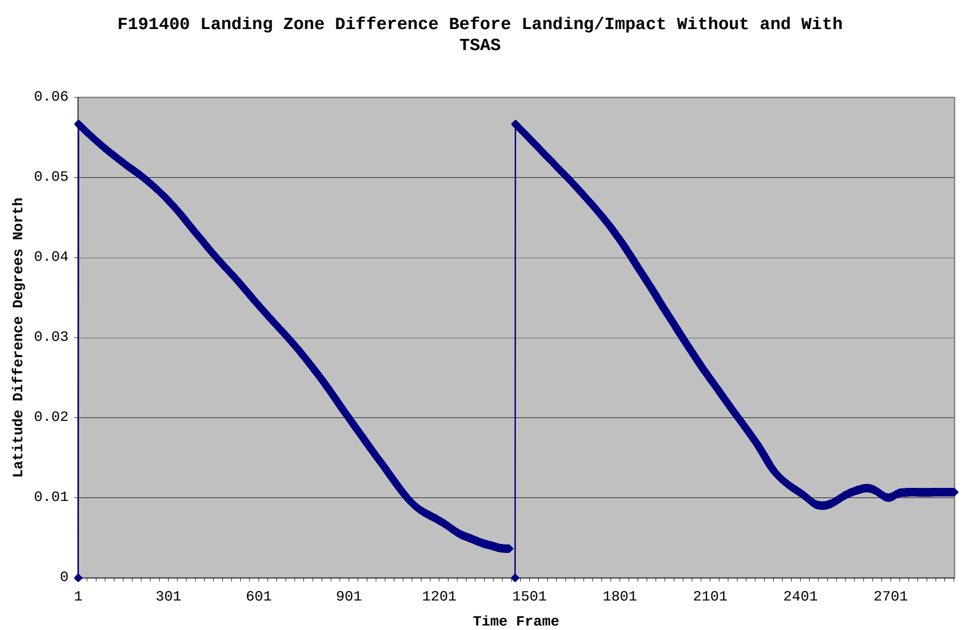

Figure 24. Participant F191400 Landing Zone Difference Plot

Table 5 containing paired interval test data reveals a positive trend by Participants to navigate closer to the landing zone with the TSAS. Decimal degree values were converted to feet using 6076 feet per one-degree latitude.

Flight Deviation From Landing Zone Using TSAS Compared to Without TSAS			
Participant	**Deviation With TSAS (deg)**	**Deviation Without TSAS (deg)**	**Difference (deg)**
M71300	-0.00319	0.05239	-0.05558
M151500	0.01197	0.01310	-0.00113
M91330	0.01853	0.01358	0.00495
F191400	0.01070	0.00364	0.00706
M161000	0.01799	0.04645	-0.02846
M151400	0.00110	0.01008	-0.00898
		Mean Difference	-0.01369
		Standard Deviation	0.02421
		Standard Error	0.00988
		df of 5 at 95%	2.015
		Margin of Error t_5	0.01992
		95% confidence	(-0.01369 +/-0.1992)
		or interval of	(-0.03361 , 0.00623) degrees
Negative differences indicated the TSAS allowed participant to get closer to the landing zone. Results indicate with 95% confident that for pilots wearing the TSAS during an approach flight after a loss of vision on average were up to 0.0331 degrees (203 feet) closer or 0.00623 degrees (37 feet) farther from the landing zone than pilots without the TSAS.			

Table 6. Landing Zone Deviation Table

Flight Profiles of the Participants provided a visual indication of how well the participant controlled decent during the approach using only the TSAS to provide cues. Figure 25 is a plot of an ideal approach assuming immediate transition time to the TSAS after a blinding event and immediate response to cues.

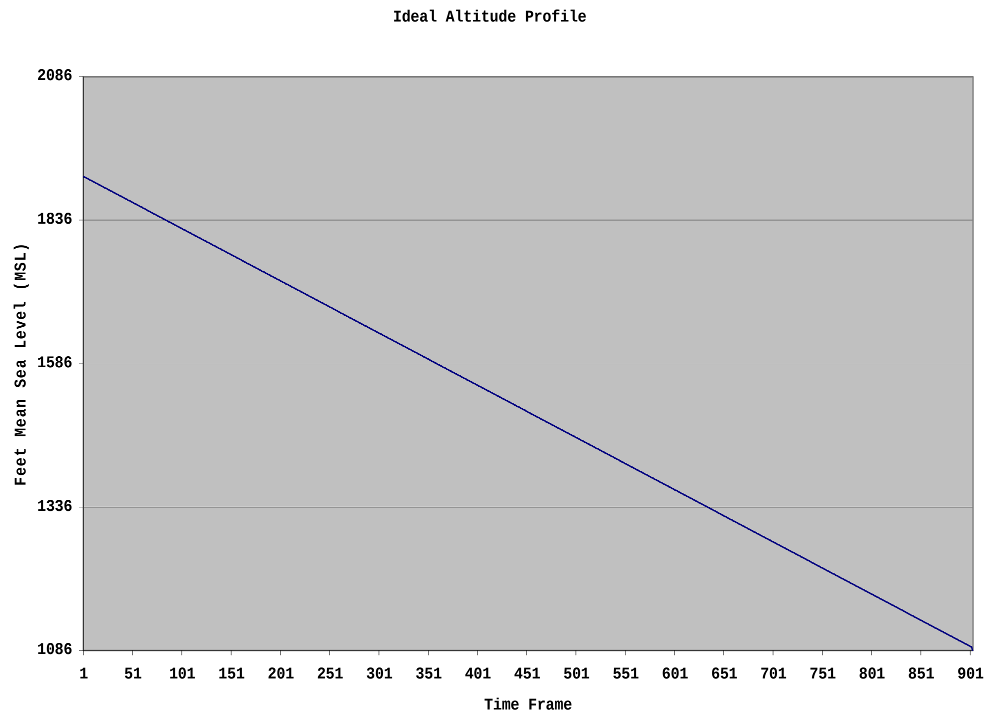

Figure 25. Ideal Approach Altitude Flight Profile

Figures 26-31 illustrate altitude approach profiles with and without the TSAS. The altitude plots revealed a tendency of the Participants to pull back on the stick and gain altitude immediately after the blinding event. This action was useful to remain clear of obstacles, however, airspeed dropped off and the aircraft rolled and descended because of the simulated reduction of aerodynamic lift necessary keep the aircraft airborne. Participants M71300 in Figure 28, M91300 in Figure 29, and M151400 in Figure 31 with the TSAS responded initially to the cues but lost control because of disorientation or reversed the inputs for the cues during the approach resulting disorientation and the aircraft crashed.

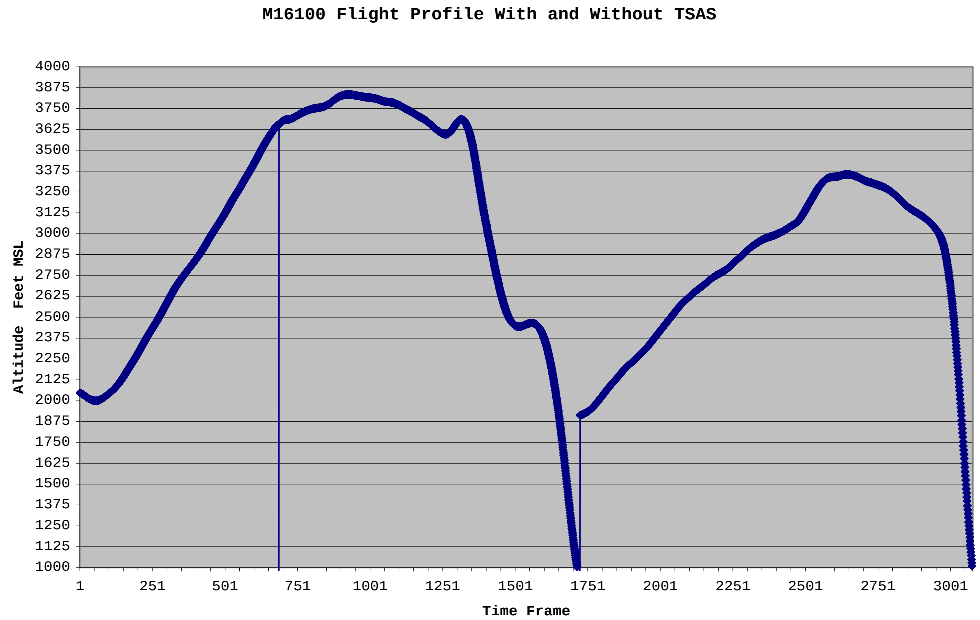

Figure 26. Participant M161000 Altitude Flight Profile

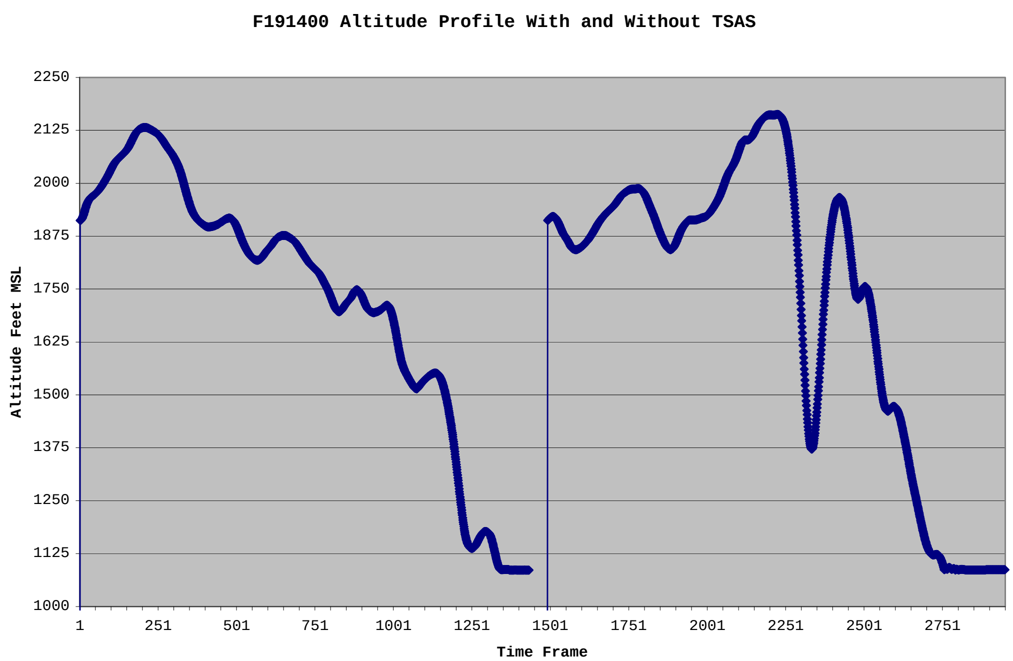

Figure 27. Participant F191400 Altitude Flight Profile

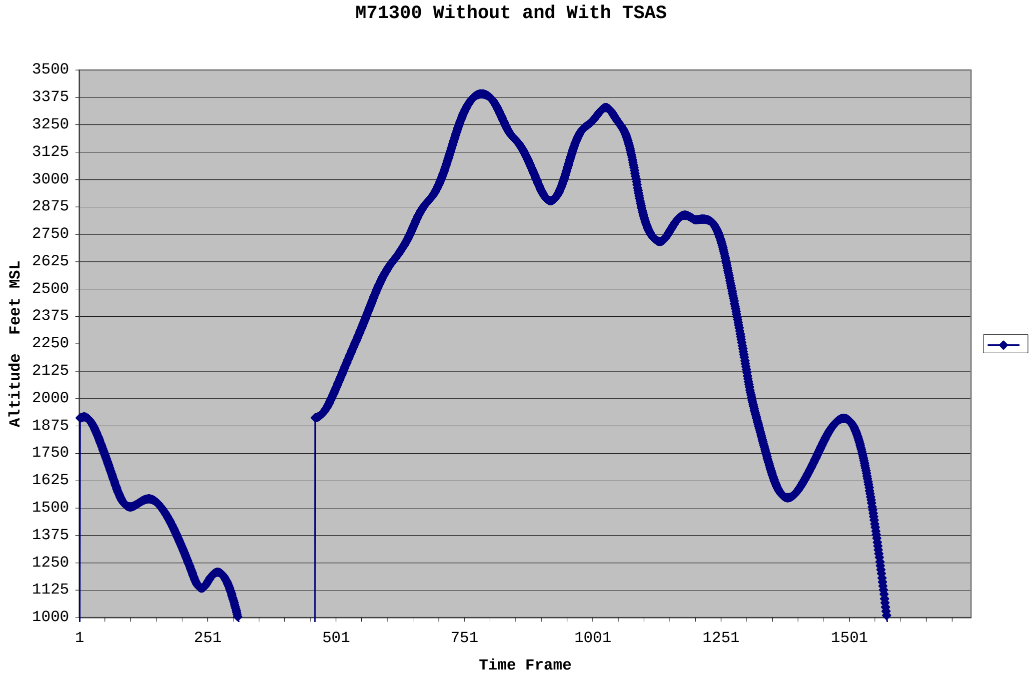

Figure 28. Participant M71300 Altitude Flight Profile

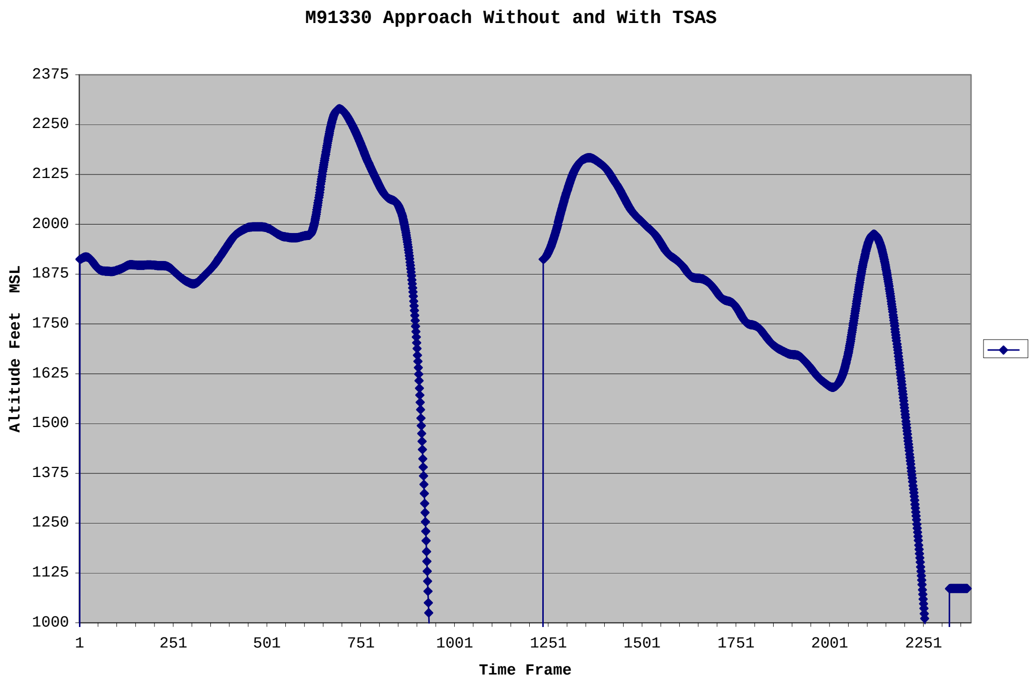

Figure 29. Participant M91330 Altitude Flight Profile

Figure 29 and Figure 30 show instances in which disorientation occurred from which recovery or a safe landing was not possible for the time remaining and proximity to terrain.

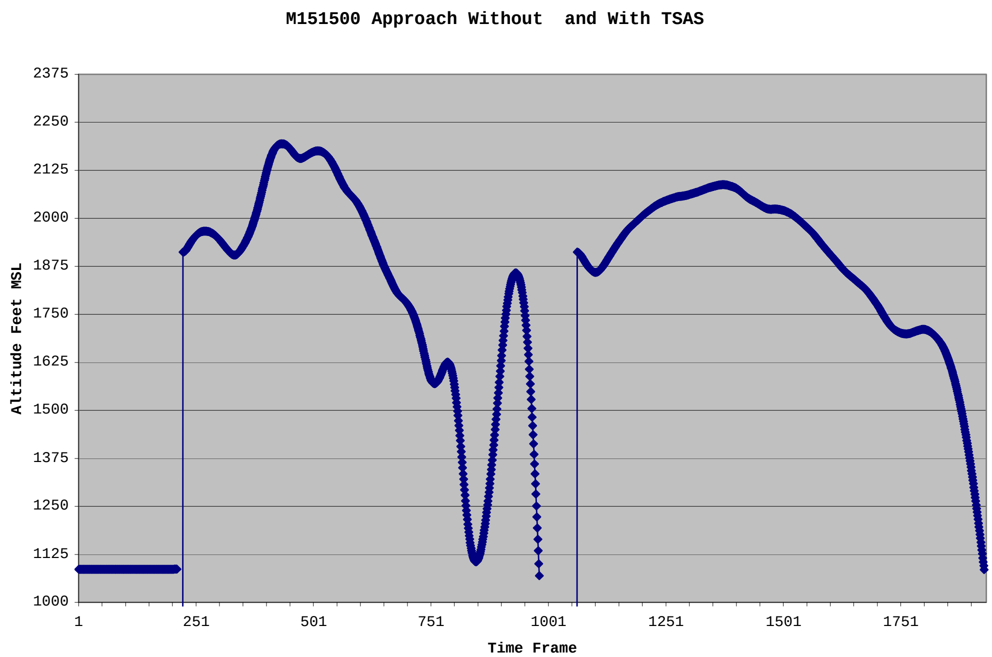

Figure 30. Participant M151500 Altitude Flight Profile

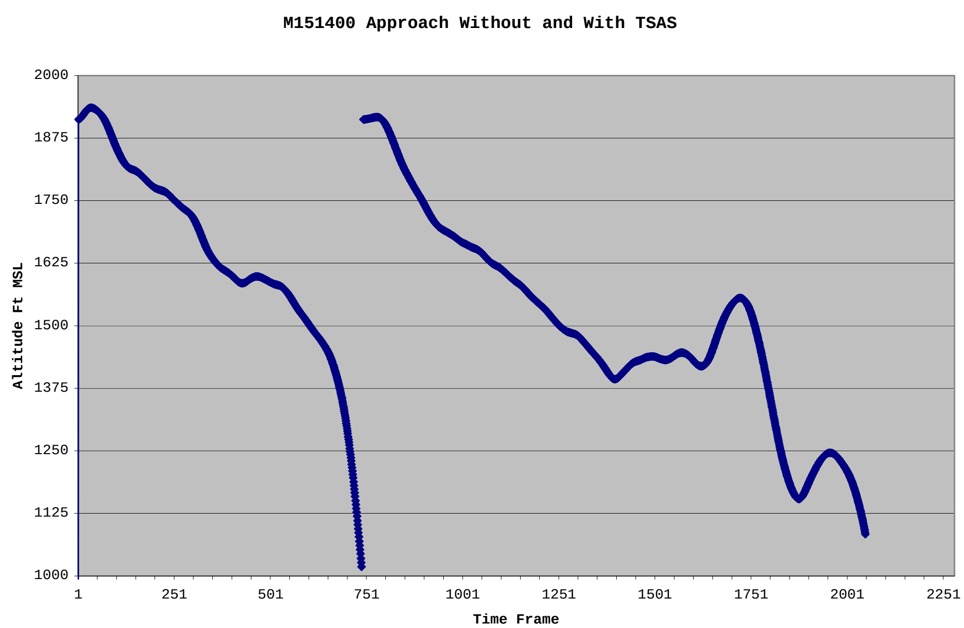

Figure 31. Participant M151400 Altitude Flight Profile

C. POST-FLIGHT QUESTIONNAIRE

After Phase 2, Participants answered a Post-Flight questionnaire (see Appendix C) to provide individual feedback. The purpose of the questionnaire was to record how each participant felt about the experiment, both with and without the vest, as well as the perceived usefulness of the TSAS. The questionnaire provided a quick check and immediate feedback concerning perceived self-improvement provided by using the TSAS. The questionnaire used a *Likert* scale with a score of one recording no improvement to a score of 10 recording a significant level of improvement. Besides improvement, the questionnaire allowed Participants to indicate a level of perceived ability to maintain a heading and to keep the aircraft out of unusual attitudes of pitch and roll. The questionnaire period provided an opportunity for the researcher to observe for simulator sickness to ensure that no symptoms existed prior to the participant leaving the experiment. None of the Participants experienced or showed signs of simulator sickness.

Non-pilot Participants required more time for the simulator familiarization portion but according to the questionnaire results, they understood the tactor input cues the same as pilots. Participants indicated haptic feedback was an interesting concept with current pilot culture receptive if given time to adjust. One pilot wanted to integrate the TSAS into the training for next generation pilots. Another suggested the tactors provided good input, but desired a variable input with frequency and strength when roll or pitch became extreme. Participants suggested adding voice for altitude and power cues to improve performance. Pilot Participants indicated the addition of a radar altimeter cue would assist them. One participant recommended a better design of cyclic pitch input because of possible confusion with roll inputs. Two Participants requested a voice headset capability to supply altitude callouts from ground radar altimeter to assist landing the aircraft. One pilot participant thought the inputs were too quick to register the input and react. The Participant attributed the comment to the training and familiarization time used for this evaluation. With a longer training period, the cognitive load decreased from familiarity with input and response recognition. Table 6 displays a summary of each Participant's response to the *Likert* scale questions. An impact prior to the airfield defined a crash during the study recorded in Table 7.

Post-Flight Questionnaire							
	With TSAS First	**Maintained Hover**	**Maintained Course**	**Understood Inputs**	**Maintained Level Attitude**	**Returned to Level Attitude**	**TSAS Helped**
M71300	x	4	4	3	4	4	4
F80800							
M91330		5	5	8	7	6	8
M161000		5	3	7	5	5	9
M151400		4	8	6	9	6	10
M151500	x	5	6	6	7	7	10
F131300							
F151300							
F191400	x	10	8	8	10	10	9
Mean		5.5	5.7	6.3	7.0	6.3	8.3
SD		0.49	1.7	1.7	1.7	1.0	2.2

Table 7. Post-Flight Questionnaire Key Responses

Participant Results In Virtual Flight Environment			
	Completed Tasks	**Crashed With TSAS**	**Crashed Without TSAS**
M71300	Yes	Yes	Yes
F80800	Yes	NA	Yes
M91330	Yes	Yes	Yes
M161000	Yes	No	Yes
M151400	Yes	Yes	Yes
M151500	Yes	No	Yes
F131300	Yes	NA	Yes
F151300	Yes	NA	Yes
F191400	Yes	No	Yes
Count	9	3	9
	Participants did not complete both parts		

Table 8. Crash Results using Prototype TSAS

Questionnaire data gave a quick indication of the benefit of the TSAS with a mean help score of 8.3 out of 10 recorded. The Participant responses confirmed the improvement recorded by comparing airfield latitude coordinates. Altitude plots revealed a trend of the pilots to pull back on cyclic and gain altitude after the simulated vision loss and then adjust to the inputs from the TSAS. Graphs depicting a rapid decrease in altitude over a short time frame indicated the time when the Participant entered an unrecoverable attitude and resulted in a simulator crash.

The documented increase in time between eight seconds and 46 seconds support the advantage of the TSAS compared to without the TSAS. The altitude figures showed a characteristic distinct gain trend in altitude of the participant after the simulated loss of vision and the visually noted difference in time before the participant entered into an unrecoverable attitude. The second spike in altitude for the participant without the TSAS was the result of participant hearing the audio sound from the speakers corresponding to increased airspeed and engine speed sounds followed by a last ditch pullback on the cyclic by participant to gain altitude. Such a move from the pilot resulted in disorientation and ultimately a crash. Clear dots indicated speed before impact was excessive. Improved accuracy navigating to the landing zone demonstrated the advantage of the TSAS to guide the aircraft and pilot over the landing zone. Such proximity is sufficient for simulated tower personnel or ground personnel to provide potential voice communications and safety talk the pilot down onto the landing zone.

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V. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

The prototype Tactile Situational Awareness System provided sufficient haptic feedback to keep three out of six Participants oriented toward the landing field without vision during an approach. Vision can be augmented using haptics and the TSAS is a candidate solution. The results of this simulator study are consistent with the findings by Cheung et al (2004) who reported the TSAS provided appropriate cues for Participants to maintain orientation. The increase in time provided by using the TSAS to augment vision is supportive of the findings of Nakagawara et al (2003) who reported visual acuity returned after an intentional blinding episode. Validation of time gained was evident in the present results by observing the paired time difference between Participants with and without the TSAS until the aircraft reached the airport.

Trend characteristics shown in the altitude plots suggested a tendency for the pilots to gain altitude to avoid obstacles on the ground. Without the TSAS providing feedback, all Participants eventually crashed. Critical flight time advantage of 8.6 to 46 seconds, noted in Table 4, allowed the Participant to maintain situational awareness because of the quick transition from vision to cues from the TSAS. In a loss or reduced vision situation, contributing to the pilot's vision recovery time was important. Navigation using heading cues from the TSAS was successful with three Participants landing on average within 83 feet of the landing zone as noted in Table 5. Participants demonstrated they correctly interpreted cues and continued flight toward the runway sufficient to reach the landing zone. Three Participants responding to the TSAS vest eventually crashed; however, three responded to cues and landed as noted in Table 8 adding hope to the value added from the TSAS to reduce Class A mishaps.

Participant feedback provided additional information. Participant M161000 said that the two back tactor signals were confusing for mental mapping during the training phase but learned where to move the controls by the actual test or second phase. Results from the Questionnaire comments noted two negative training consequences -- reversal of the two back inputs and applying reverse flight control input. With more research and added voice feedback, it may be possible to prevent undesired or reverse control input. As a training tool, Participants adapted to TSAS cues easily. Simulator training with the TSAS can provide a tactile training aid for instructors to correct common student pilot errors without physical hands on methods. Applications for the TSAS during brown out, white out, and laser conditions have excellent potential as a haptic instrument to maintain orientation and reduce or prevent low visibility related Class A mishaps.

Observed learning by Participants during the familiarization phase demonstrated that use of the TSAS prototype was easy to learn. The familiarization and training phase allowed the Participants to map the tactor inputs to flight control inputs. Participant M151500 felt the TSAS was an interesting concept and admitted prior training instinctively triggered a desire to continue scanning inside for the instruments after vision was lost. Using the TSAS allowed for an alternative method to support vision, which remains the primary method for pilots to obtain safety of flight information. Transfer of the TSAS prototype and integrating it with the computer system of a fully functioning aircraft is promising given that more aircraft control inputs are fly-by-wire.

Confirmation of the need for the development of a situational awareness or disorientation warning device such as the TSAS as an aid for pilots appeared in a message in October 2008 after the Program Objective Memorandum (POM-12) Aircrew Systems (ACS) Enabler Naval Aviation Requirements Group (NARG) meeting. One of the results of the meeting included:

> Spatial Disorientation Warning Device – Spatial disorientation is a major human factor that contributes to present day mishaps. Recommend the development of a device that will provide sensory stimulation in response to a spatial disorientation event that will provide sensory stimulation in response to a spatial disorientating event.

B. RECOMMENDATIONS

Continue testing changes in technology to improve human machine interoperability. The first is to determine how small a degree change in heading the average person can control using TSAS. Second, investigate the level of heading control in a blind condition with the TSAS combined with the benefit of voice heading cues to compliment the tactile cues. For altitude control, a third recommendation is to incorporate an additional input tied to the radar altimeter to set and monitor an altitude and have tactor cues alert the pilot if above or below a desired altitude. An example of an altitude control situation is night flight over water or over terrain to avoid power lines or obstacles. Applying the TSAS with Autonomous Aerial Vehicle (AAV) ground operators is promising to help lower the number lost because of not knowing the correct orientation during flight. The use of X-Plane allows repeating the experiment model and simulating a gradual restoration of scenery after thirty seconds and monitor recover techniques from loss of sight as mentioned by the FAA laser test study (Nakagawara et al (2003). This thesis hopes to contribute to a solution to the laser blindness threat to military, commercial and general aviation. If advances in technology continue, the aviation and unmanned vehicle community stand to gain if TSAS procedures are approved and placed in NATOPS manuals and FAA aeronautical manuals.

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APPENDIX A: CODE FILES

File: tactor.py
Language: Python
Compiler: Eclipse 3.2
Developed by J. S. Brown and Randy Jones

```
import threading, time

EAI_COMMAND_OK = '\x80'
EAI_DEFAULT_FREQUENCY = 258   # Tactor Frequency in Hz
MAX_ON_TIME = 1000            # Time in milliseconds
TACTOR_SHOT_1 = chr(0)        # 0 corresponds to
device 1
TACTOR_SHOT_2 = chr(1)        #
TACTOR_SHOT_3 = chr(2)
TACTOR_SHOT_4 = chr(3)
TACTOR_LEFT_SHOULDER = chr(4)
TACTOR_RIGHT_SHOULDER = chr(5)
TACTOR_DISTANCE_1 = chr(6)
TACTOR_DISTANCE_2 = chr(7)
TACTOR_DISTANCE_3 = chr(8)
TACTOR_DISTANCE_4 = chr(9)

class commander(threading.Thread):
   def __init__(self, serialPort):
      threading.Thread.__init__(self)
      self.setDaemon(True) # Daemon threads stop with
main thread
      self.serial_port = serialPort
      self.serial_port.write('\x21')
      self.stop = False
      self.on = [False, False, False, False, False,
                 False, False, False, False, False]
      self.seconds = 0

   def TurnOn(self, tactor, time):
      if( time > MAX_ON_TIME ):
         time = MAX_ON_TIME
      self.serial_port.write('\x11' + tactor +
chr(time/10))

   def TurnLeft(self):
      global TACTOR_LEFT_SHOULDER
      self.TurnOn(TACTOR_LEFT_SHOULDER, 50)
```

```
def TurnRight(self):
   global TACTOR_RIGHT_SHOULDER
   self.TurnOn(TACTOR_RIGHT_SHOULDER, 50)

def end(self):
   self.serial_port.close()
   self.stop = True

def run(self) :
   while not self.stop :
      time.sleep(2.0)
      if (self.stop):
         break
      i = 0;
      for turn_on in self.on:
         if turn_on:
            print i, "on"
            self.TurnOn(chr(i), 100)
         i = i + 1
      self.seconds = self.seconds + 2
      print self.seconds, "seconds"
```

File: udp.py
Language: Python
Compiler: Eclipse 3.2
Developed by James S. Brown and Randy Jones

```
from socket import *
import threading, struct
from geo_helper import calculate_distance_and_bearing

ValueMap = dict()

### This thread receives UDP data from X-Plane output ###

class listener(threading.Thread) :
   def __init__(self, ioPort, tactor, uidata):
      threading.Thread.__init__(self)
      self.tactor = tactor
      self.uidata = uidata
      self.SOCKET=socket(AF_INET, SOCK_DGRAM)
      self.SOCKET.bind(('',int(ioPort)))
      self.setDaemon(True)
 ### Daemon threads stop with main thread ###
      self.stop = False
      self.prev_rudder = 0.0
      self.heading = None
      self.prevHeading = None
      self.off = 0
      self.lat = None
      self.long = None

### Output screen data display X-Plane feed received ###
def dumpData(self, data):
      i = 0
      for c in data:
         i = i + 1
         print '%02X' % ord(c),
      if (i % 20) == 0:
         print ""
      print ""

   def end(self):
      self.stop = True
      self.SOCKET.shutdown(SHUT_RDWR)
      self.SOCKET.close()
      self.tactor.end()
```

```
   def RollControl(self, roll):
      THRESHOLD = 7.0
  ### Max roll degrees before cue received by operator ###
      ### print "roll control", roll ###
      if (roll > THRESHOLD):
         self.tactor.on[0] = True
         self.tactor.on[1] = False
      elif (roll < -THRESHOLD):
         self.tactor.on[0] = False
         self.tactor.on[1] = True
      else:
         self.tactor.on[0] = False
         self.tactor.on[1] = False

   def PitchControl(self, pitch):
    ### print "roll control", pitch ###
      if (pitch > 20):
         self.tactor.on[2] = True
         self.tactor.on[3] = False
      elif (pitch < -8):
         self.tactor.on[2] = False
         self.tactor.on[3] = True
      else:
         self.tactor.on[2] = False
         self.tactor.on[3] = False

   def AntiTorq(self, hdg):
      THRESHOLD = 4.0
     ### tolerance plus and minus 4 deg hdg before cue ###
      if self.heading == None:
         self.heading = hdg
         self.prevHeading = hdg
         self.off = 0
      else:
         ### adjust for 359/0 transition ###
         if (hdg - self.prevHeading) > 180:
            self.off = self.off + 360
         elif (hdg - self.prevHeading) < -180:
            self.off = self.off - 360
         # heading trigger calculation
         dif = self.heading - hdg + self.off
         print self.heading, hdg, self.off, dif,
self.prevHeading
         if dif > THRESHOLD:
            self.tactor.on[8] = False
            self.tactor.on[9] = True
```

```
            elif dif < (-1*THRESHOLD):
                self.tactor.on[8] = True
                self.tactor.on[9] = False
            else:
                self.tactor.on[8] = False
                self.tactor.on[9] = False
            self.prevHeading = hdg

    def procData(self, data):
        BLEN = 6
        XLEN = 36
        global ValueMap
        qty = (len(data) - 6) / XLEN
        for i in xrange(qty):
            id = data[BLEN+(XLEN*i):BLEN+(XLEN*i)+4]
            id = struct.unpack('i', id)
            id = id[0]
            substr = data[BLEN+4+(XLEN*i):BLEN+4+(XLEN*i)+32]
            values = struct.unpack('8f', substr)
            ValueMap[id] = values
       ### Look for hdg change from X-Plane Index 16 ###

        if self.uidata.AntiTorqOn:
            self.AntiTorq(ValueMap[16][2])
        else:
            self.heading = None
            self.tactor.on[8] = False
            self.tactor.on[9] = False

       ### Look for Roll value from Level horizon ###
        if self.uidata.RollControlOn:
            self.RollControl(ValueMap[16][1])
        else:
            self.tactor.on[0] = False
            self.tactor.on[1] = False

       ### Look for Pitch value from Level horizon ###
        if self.uidata.PitchControlOn:
            self.PitchControl(ValueMap[16][0])
        else:
            self.tactor.on[2] = False
            self.tactor.on[3] = False

    def run(self) :
        while not self.stop : # Receive in daemon thread
            data, address = self.SOCKET.recvfrom(1024)
```

```
        if data and data[0:4] == "DATA":
            self.procData(data)
    self.SOCKET.close()
```

File: Xplane.py
Language: Python
Compiler: Eclipse 3.2

```
## This class allows user to activate Tactor Suit ##

import wx, wx.lib.newevent
import sys, os.path, threading, time, serial
import udp, tactor

tactor_task = None
udp_task = None

# Initial Status Assignments #

class UIdata:
    AntiTorqOn = False
    RollControlOn = False
    PitchControlOn = False

uidata = UIdata()

# Create GUI interface and labels #

class MainFrame(wx.Frame):
    def __init__(self, parent=None, id=-1,
    pos=wx.DefaultPosition,
    title="NPS - X-Plane Tactor Program"):
    wx.Frame.__init__(self, parent, id, title, pos,
    size=(400, 300))
        panel = wx.Panel( self, -1 )
        vs = wx.BoxSizer( wx.VERTICAL )
        hs = wx.BoxSizer( wx.HORIZONTAL )
        vs.Add(hs, 1, wx.ALIGN_CENTRE|wx.ALL, 5 )

        # X-Plane interface
 box1_title = wx.StaticBox( panel, -1,"X-Plane Interface" )
        box1 = wx.StaticBoxSizer( box1_title, wx.VERTICAL )
        grid1 = wx.FlexGridSizer( 0, 2, 0, 0 )
        label11 = wx.StaticText(panel, -1, "IP Port")
        grid1.Add( label11, 0,
        wx.ALIGN_CENTRE|wx.LEFT|wx.RIGHT|wx.TOP, 5 )
        self.text11 = wx.TextCtrl( panel, -1, "4000" ,
        style=wx.TE_RIGHT)
        grid1.Add( self.text11, 0,
        wx.ALIGN_CENTRE|wx.LEFT|wx.RIGHT|wx.TOP, 5 )
```

```
        box1.Add( grid1, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        hs.Add( box1, 1, wx.ALIGN_CENTRE|wx.ALL, 5 )

# Tactor interface
        box2_title = wx.StaticBox( panel, -1, "Tactor Vest
        Interface" )
        box2 = wx.StaticBoxSizer( box2_title, wx.VERTICAL )
        grid2 = wx.FlexGridSizer( 0, 2, 0, 0 )
        label21 = wx.StaticText(panel, -1, "Serial Port")
        grid2.Add( label21, 0,
        wx.ALIGN_CENTRE|wx.LEFT|wx.RIGHT|wx.TOP, 5 )
        ports = ["COM1", "COM2", "COM3", "COM4", "COM5",
        "COM6", "COM7", "COM8", "COM9"]
        self.combo21 = wx.ComboBox(panel, -1, "COM1", (90,
        50), (95, -1),ports, wx.CB_DROPDOWN|wx.CB_READONLY)

        grid2.Add( self.combo21, 0,
        wx.ALIGN_CENTRE|wx.LEFT|wx.RIGHT|wx.TOP, 5 )
        box2.Add( grid2, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        hs.Add( box2, 1, wx.ALIGN_CENTRE|wx.ALL, 5 )

# test
        box3_title = wx.StaticBox( panel, -1, "Vest Test" )
        box3 = wx.StaticBoxSizer( box3_title, wx.VERTICAL )
        grid3 = wx.FlexGridSizer( 0, 3, 0, 0 )
        #self.combo22 = wx.ComboBox(panel, -1, "1",(70,
50),
        #    (95, -1), xrange(11),
wx.CB_DROPDOWN|wx.CB_READONLY)
        time = ['1', '2', '3', '4', '5', '6', '7', '8',
'9', '10']
        self.combo22 = wx.ComboBox(panel, -1, '1', (100,
50),
            (95, -1), time)
        self.combo22.SetSelection(0)
        stuff2 = ["shot1", "shot2", "shot3", "shot4", "left
shoulder","right shoulder", "distance1", "distance2",
"distance3", "distance4"]

# new stuff
        stuff = ["UpperLeft 1", "UpperRight 2",
"UpperRightBack 3", "UpperLeftBack 4", "LowerLeftFront 5",
"LowerRightBack 6", "LowerLeft 7", "LowerRight 8", "LeftLeg
9", "RightLeg 10"]
 self.combo23 = wx.ComboBox(panel, -1, "UpperLeft 1", (100,
50), (95, -1), stuff, wx.CB_DROPDOWN|wx.CB_READONLY)
```

```
        grid3.Add( self.combo23, 0,
wx.ALIGN_CENTRE|wx.LEFT|wx.RIGHT|wx.TOP, 5 )
        grid3.Add( self.combo22, 0,
wx.ALIGN_CENTRE|wx.LEFT|wx.RIGHT|wx.TOP, 5 )
        self.tb = wx.Button(panel, -1, "test")
        grid3.Add (self.tb, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        self.Bind(wx.EVT_BUTTON, self.test, self.tb)
        box3.Add( grid3, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        vs.Add( box3, 1, wx.ALIGN_CENTRE|wx.ALL, 5 )

# Anti-Torque button
        self.ab = wx.Button(panel, -1, "Anti-Torq (OFF)")
        vs.Add (self.ab, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        self.Bind(wx.EVT_BUTTON, self.antiTorq, self.ab)

# roll control button
        self.rc = wx.Button(panel, -1, "Roll-Control
        (OFF)")
        vs.Add (self.rc, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        self.Bind(wx.EVT_BUTTON, self.RollControl, self.rc)

# roll control button
        self.pc = wx.Button(panel, -1, "Pitch-Control
        (OFF)")
        vs.Add (self.pc, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        self.Bind(wx.EVT_BUTTON, self.PitchControl,
        self.pc)

# Start button
        self.sb = wx.Button(panel, -1, "START")
        vs.Add (self.sb, 0, wx.ALIGN_CENTRE|wx.ALL, 5 )
        self.Bind(wx.EVT_BUTTON, self.start, self.sb)

# Roll, Pitch, and Anti-Torque label
        panel.SetSizer( vs )
        vs.Fit( panel )
        self.panel = panel

    def RollControl(self, event):
        global uidata
        uidata.RollControlOn = not uidata.RollControlOn
        if uidata.RollControlOn:
           self.rc.SetLabel("Roll-Control (ON)")
        else:
           self.rc.SetLabel("Roll-Control (OFF)")
```

```
    def PitchControl(self, event):
        global uidata
        uidata.PitchControlOn = not uidata.PitchControlOn
        if uidata.PitchControlOn:
           self.pc.SetLabel("Pitch-Control (ON)")
        else:
           self.pc.SetLabel("Pitch-Control (OFF)")

    def antiTorq(self, event):
        global uidata
        uidata.AntiTorqOn = not uidata.AntiTorqOn
        if uidata.AntiTorqOn:
           self.ab.SetLabel("Anti-Torq (ON)")
        else:
           self.ab.SetLabel("Anti-Torq (OFF)")

    def test(self, event):
        if tactor_task == None:
            dlg = wx.MessageDialog(self, 'Stopped, start to
test.',
                     'Error', wx.OK | wx.ICON_INFORMATION)
            dlg.ShowModal()
            dlg.Destroy()
            return
        sensor = chr(self.combo23.GetSelection())
        print self.combo22.GetSelection()
        time = self.combo22.GetSelection() * 100
        tactor_task.TurnOn(sensor, time)

    def start(self, event):

# set up serial port
        global tactor_task, udp_task, uidata
        sel = self.combo21.GetSelection()
        serial_port = None
        if udp_task != None:
            udp_task.end()
        try:
            serial_port = serial.Serial(sel)
        except:
            print sys.exc_info()[0]
        if serial_port == None:
            s = self.combo21.GetValue()
            dlg = wx.MessageDialog(self, 'Could not
            intialize ' + s + '.',
                     'Error', wx.OK | wx.ICON_INFORMATION)
```

```
            dlg.ShowModal()
            dlg.Destroy()
        else:
            self.sb.SetLabel("STOP")
            self.Bind(wx.EVT_BUTTON, self.stop, self.sb)
            udp_port = self.text11.GetValue()
            tactor_task = tactor.commander(serial_port)
            tactor_task.start()
            udp_task = udp.listener(udp_port, tactor_task,
            uidata)

          udp_task.start()

    def stop(self, event):
        global tactor_task, udp_task
        udp_task.end()
        udp_task = None
        tactor_task.end()
        tactor_task = None
        self.sb.SetLabel("START")
        self.Bind(wx.EVT_BUTTON, self.start, self.sb)

class App(wx.App):
    def OnInit(self):
        self.frame = MainFrame()
        self.frame.Show()
        self.SetTopWindow(self.frame)
        self.frame.Centre()
        return True

def getDir():
    if os.path.isdir(sys.path[0]):
        dir = sys.path[0]
    else:
        dir = os.path.dirname(sys.path[0])
    return dir + '/'

def main():
    global app
    app = App(0) # call with 0 to get debug message to
sysout
    app.MainLoop()

if __name__ == '__main__':
    main()
```

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APPENDIX B: PRE-FLIGHT QUESTIONNAIRE

Q1: Do you play computer or flight simulator video games?

Yes☐ or No☐

Q2: How many hours a week do you play?

< 5 hrs ☐ or > 5 hrs ☐ NA ☐

Q3: Are you susceptible to motion sickness or get sick from video games?

Yes☐ No☐

Q3a: If yes, please explain.

Q4: How old are you? _______________ years

Q5: Please mark your sex. Male ☐ or Female ☐

Q6: What is your dominant writing hand?

Right Hand ☐ or Left Hand ☐

Q7: Are you colorblind?

Yes ☐ or No ☐

Q7 a: If color blind, which color or colors?

Red☐, Orange☐, Yellow☐, Green☐, Blue☐, Purple☐

Other _______

Q8: Do you have any flying experience in a helicopter, airplane or glider?

Yes ☐ or No ☐

Q8 a: If yes, check type and fill in how many hours flight time?

Helicopter ☐ ___________Hours Flight Time

Airplane ☐ ___________Hours Flight Time

Glider ☐ ___________Hours Flight Time

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APPENDIX C: POST- FLIGHT QUESTIONNAIRE

Instructions: Please answer the following questions. One(1) represents lowest score and ten(10) best score.

1. Please check if you conducted flight with TSAS first or without TSAS first?

   a. TSAS First ☐

   b. Without TSAS ☐

2. Rate how well you were able to turn left and right using the input device?

   1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

3. How well were you able to maintain a hover with TSAS?

   1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

4. How well were you able to maintain heading with TSAS?

   1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

5. How well were you able to understand input signals from TSAS?

   1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

6. How well were you able to remain wings level or on a level horizon with input device?

   1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

7. How well were you able to return to wings level or to a level horizon with input device?

   1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

8. Your role in the scene was to either maintain a hover or follow a heading signal to an airfield. How well to you feel the TSAS helped compared to without the TSAS?

1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

Comment____

9. Did you feel any type of simulator sickness during the test?

Yes ☐ No☐

If yes, rate level of simulator sickness and duration in minutes?

1☐ 2☐ 3☐ 4☐ 5☐ 6☐ 7☐ 8☐ 9☐ 10☐

Duration of feeling simulator induced sickness __________minutes.

10. Please check if you were able to accomplish the following initial tasks:

Task 1. Were you able to maintain altitude? Yes☐ No☐

Task 2. Did you crash the simulator without TSAS? Yes ☐ No ☐

Task 2a. Did your crash with TSAS? Yes ☐ No ☐

Task 3. Did you maintain the navigation radial to the airfield from (starting point)? Yes ☐ No.☐

Task 4. Were you able to navigate back to course assigned? Yes ☐ No ☐

11. Which Task did you omit during the study?

1☐ 2☐ 3 ☐ 4☐ 5 ☐ N/A ☐

APPENDIX D: INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

Naval Postgraduate School
Institutional Review Board (IRB)

18-Jan -07

From: LT Brent Olde, Ph.D.
To: Research Assistant Professor William Becker
Research Professor Michael McCauley
LCDR James S. Brown

Subject: YOUR PROJECT: EVALUATION OF TACTILE SITUATION AWARENESS SUIT TO AUGMENT VISION AND IMPROVE SPATIAL ORIENTATION IN A VIRTUAL ENVIRONMENT

1. The NPS IRB is pleased to inform you that the NPS Institutional Review Board has approved your project (NPS IRB# NPS20070031).

2. The NPS IRB was originally certified by BUMED on 26 July 2002 and has been re-certified until 30 March 2007.

3. This approval is valid for one year from this date. Please submit a copy of all records and consent forms to the Research and Sponsored Programs Office (Laura Ann Small, Halligan Hall, Room 201B) at the conclusion of this project.

4. If your protocol changes at any time, you will need to resubmit your project proposal to the NPS IRB.

Sincerely,

Lt Brent Olde, Ph.D.
Chair
NPS Institutional Review Board

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